

**THE EFFECT OF ALTITUDE ON THE PERFORMANCE
OF A SPARK IGNITION ENGINE
USING AN ALCOHOL-BLENDED FUEL**

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**Submitted to the University of Cape Town
in half fulfilment for the degree of
Master of Science in Engineering**

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ABSTRACT

It is known that altitude influences both the performance and octane requirement of automotive engines. With the peculiar elevated geography in South Africa, there has been concern of the effects of altitude on automotive engines, when driving between the coast and the Highveld.

This thesis describes an experimental investigation into the effects of altitude on a locally mass-produced spark ignition engine, operating under three different carburation settings. Tests have been performed in an altitude simulation dynamometer test cell. Comparative assessments are made of the effects of altitude on fuel economy, exhaust CO emission and engine knock response in terms of knock-limited spark advance with a straight gasoline and a 10% ethanol blend.

It has been shown that the extent of the altitude effects on fuel economy and exhaust CO emission strongly depends on the operating carburation set points. Based on the experimental results, it was found that the use of the 10% ethanol blend could not change the extent of the altitude effects on the engine. However, compared to the straight gasoline, the ethanol blend decreased the influences of altitude with lower CO emission and improved fuel economy, as a result of the mixture leaning effect.

The increase in knock protection with altitude was evident from the test results. It was found that compared to the straight gasoline, the ethanol blend has a higher anti-knock quality, in terms of the degree of knock protection, at low engine speed. However, the gain in knock protection by the ethanol blend was found to decrease significantly with an increase in engine speed and marginally with a rise in altitude.

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University of Cape Town

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NOMENCLATURE

Symbols

A/F	Air/fuel ratio
CO	Carbon monoxide
E	Brake torque or enrichment
E_f	Friction loss torque
E_p	Pumping loss torque
F/A	Fuel/air ratio
h	Altitude
HC	Unburned hydrocarbon
NO	Nitrogen oxide
ON	Octane number
P	Pressure
P_d	Dry air pressure
r_c	Compression ratio
T	Temperature
γ	Ratio of specific heat capacity C_p/C_v
η_{fi}	Fuel conversion efficiency
η_t	Thermal efficiency
η_v	Volumetric efficiency
τ	Ignition delay
ϕ	Fuel/air equivalence ratio
ρ	Density
$^{\circ}\text{CA}$	Crank angle degree

Subscripts

0	Standard or sea level conditions
s	Stoichiometric
z	Altitude conditions

Abbreviations

AKI	Anti-knock index, $(RON+MON)/2$
ASTM	American society for testing and materials
BOV	Blending octane value
BSFC	Brake specific fuel consumption
BTDC	Before top dead centre
CFR	Cooperative fuels research
CRC	Coordinating research council
IMEP	Indicated mean effective pressure
ISFC	Indicated specific fuel consumption
KLSA	Knock limited spark advance
MBT	Maximum brake torque
MON	Motor octane number
RON	Research octane number
SI	Spark ignition
TDC	Top dead centre
WOT	Wide open throttle

CHAPTER 1

INTRODUCTION

1.1 Background

Two distinct combustion systems, viz. the spark ignition (SI) engine and the compression ignition engine, more commonly known as diesel engine, are employed in automotive applications. Despite the higher efficiency of the diesel engine to spark ignition engine, the latter is still dominant in personal land mobility.

Ever since the inception of the Otto four-stroke engine cycle in the spark ignition engine, engineers have been trying to improve its performance. Theoretically, the power output and efficiency attainable from the Otto cycle can be increased by using higher compression ratio. However, the phenomenon of engine knock places a limitation on the compression ratio. Despite decades of research, there is, as yet, no full understanding of the knock phenomenon over the full range of engine conditions at which it occurs. As a result, automotive manufacturers have had limited success in avoiding the constraints that knock places on performance by changing their engine designs or fuels. The only sure prevention technique is to lower the engines' compression ratios and retard the spark timing. Nowadays, the SI engine in a typical production vehicle is operated at a compression ratio in the range of 8:1 to 10:1 and with spark timing retarded from the maximum brake torque (MBT) timing. Typical spark-advance schedule for avoiding engine knock is shown in *Figure 1.1*. The loss in engine torque as the result of retarded spark timing is apparent.

On the other hand, with a fixed compression ratio, the maximum power an engine can deliver is limited by the amount of fuel that can be burned efficiently inside the engine cylinder. This is limited by the amount of air that is introduced into each cylinder every cycle. On this account, altitude imposes a direct effect on power reduction in an engine through the reduction in inlet air density, caused by reduced atmospheric pressure.

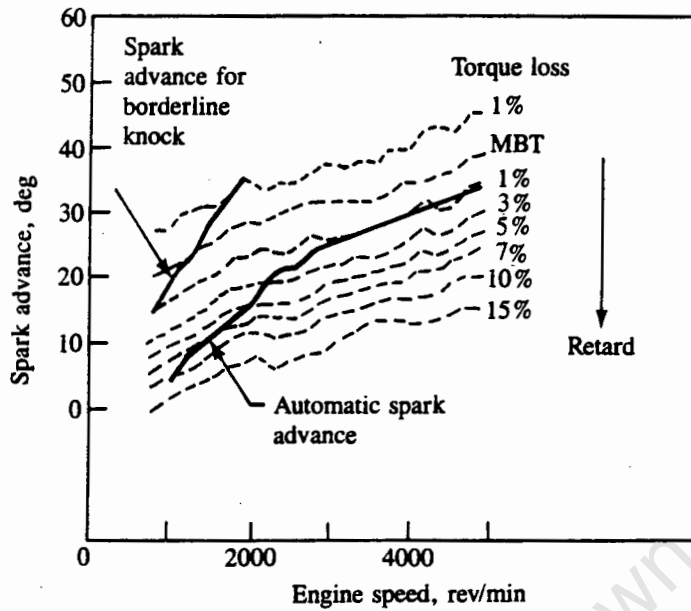


Figure 1.1 Typical spark-advance schedule to avoid engine knock problems^[8]

Although various techniques of supercharging and turbocharging have been developed to boost the engine power by compressing inlet air to higher density, such applications are limited to aircraft engines and high performance racing-car engines. Most of the modern production automobiles are still equipped with naturally aspirated engines. The deterring effect of altitude on engine power is, therefore, particularly significant for vehicles operating in mountainous areas.

The reduction of air density with altitude may also upset the mixture strength delivered to the cylinders in a SI engine. The conventional float-type carburettor inherently meters fuel flow in proportion to air volume flow rate, though, the actual mixture requirement of an engine should be on a mass basis. Thus the metering of fuel and air in such carburation system is inevitably affected by the change in air density, owing to the variations in atmospheric pressure as a result of change in altitude. Consequently, there is an enrichment effect to the combustion mixture with an increase in altitude. In general, if an engine tuned at sea level is operated at high altitude, reduction in power and fuel economy will ensue. Moreover, more severe CO and HC exhaust emissions are expected.

While imposing the above adverse effects, altitude offers one advantage. The reduction in atmospheric pressure, and hence compression pressure, with altitude decreases the octane number requirement of an engine. Initial observations on the reduction of engine octane number requirement with altitude were made in the 1940s^[1]. This reduction in Octane offers a potential benefit that allows refiner to market gasoline with lower octane number in the high-altitude areas and thus reduce the refinery cost in those regions. Since the 1940's research, the effect of altitude upon the octane number requirement has been investigated by various research groups, particularly, by those in the petroleum industry. From the previous work, it appeared that it is difficult to arrive at a universal octane correction for altitude which could be applied to any given country. The effect depends greatly on the vehicle design, technology and the composition of fuel being used. Based on the CRC altitude octane requirement program^[2], the current ASTM specification allows reductions of 1.0 to 1.5 antiknock index (AKI) per 1000 feet (300 metres)^[3] in the USA.

In South Africa, the impacts of altitude on automobile engines are of practical concern due to the elevated geography of part of the country. More than 60% of the total vehicle population is being operated at an altitude higher than 1000 m and the rest 40% are used at sea level. Owing to the split of vehicle population into high altitude and sea level, the petroleum companies produce gasoline with various octane numbers (RON) in different regions. Thus 97 premium and 93 regular gasoline are available at the coastal areas while 93 premium and 87 regular are being sold at the reef. This is equivalent to an antiknock index reduction of 0.8 per 300 m. Undoubtedly, this is to take advantage of reduction in octane number requirement with altitude and hence reduce refinery cost for the reef areas. On the other hand, vehicles from those areas can easily reach the coastal area with fuel of lower octane number before refilling with higher octane fuel. The use of lower octane number gasoline in the reef areas, thus, raises a question: Can the octane number requirement of the engine be satisfied by the reef fuel at lower altitude? If not, the vehicle will be subject to engine knock.

Generally, depending on the driving mode, two types of engine knock can be experienced. Accelerating knock occurs during a wide open throttle acceleration, which is usually transient. Although accelerating knock does not persist long enough to give rise to conditions likely to cause engine damage, the induced noise is unpleasant to the driver. On the other hand, during a period of sustained high speed on the road, the engine may be running in a severe knocking condition for a considerable time and provokes engine damage without the driver being aware of knock occurring.

A local investigation of the effect of altitude is necessitated by the fact that vehicle technology and fuel composition in this country is different from those in the USA or Europe. Vehicles with sophisticated electronic engine management systems, which control the air/fuel mixture and spark timing so as to provide optimum performance and fuel consumption, have been introduced into the US market since the 1980s. With these vehicles, the altitude effect could be minimized. However, vehicles with engine management systems are not yet widely adopted in this country. Moreover, in this country, some of the fuel supplied at the reef is different in origin from that in the coastal area. Along the coast, gasoline is crude oil derived, while on the reef some of it is derived from coal, which has a higher olefinic content. Until recently, the reef gasoline was blended with 8 percent ethanol and 2 percent higher alcohols.

While a complete answer to the above question demands a national-wide altitude octane requirement programme, this study aims at a general understanding of the effect of altitude. An altitude test cell, which can simulate pressure condition up to an elevation of 1500 m, has been constructed and tested at the Energy Research Institute by Mearns^[4]. With this test facility, the effect of altitude can be studied by dynamometer engine test under a controlled environment.

1.2 Objectives

The objective of this study is to investigate the effects of altitude on a naturally aspirated spark ignition engine, with particular attention to engine knock response, in terms of knock-limited spark advance. Engine tests are carried out with a straight gasoline and with a 10 percent alcohol-blended fuel. The aim is, firstly, to provide an understanding of altitude effect on a naturally aspirated spark ignition engine. Secondly this study attempts to reveal if there is any difference between using straight gasoline and the alcohol blend with changes in altitude.

1.3 Thesis Outline

Chapter 2 is a literature overview which consists of three parts. Part one discusses the effect of altitude on engine performance. Particular attention is given to the altitude effect on the carburation system, with respect to the effect of mixture composition on engine performance. Part two provides a fundamental background on engine knock in SI engines. The various altitude octane number requirement surveys are reviewed. Part three discusses the advantages of alcohol-blended fuels in terms of mixture leaning effect and improvement in anti-knock quality. The development of the engine test matrix in the investigation, experimental set-up and procedure are described in chapter 3. A method of measuring engine knock response, in terms of knock-limited spark advance, is also discussed. The results of the experiments are presented and discussed in chapter 4. Finally, conclusions of the investigation are discussed in chapter 5.

CHAPTER 2

LITERATURE OVERVIEW

As discussed in the previous chapter, the importance of altitude on spark ignition engine is due to its effect on engine performances and, more importantly, to concerns of engine knock, as a result of the split in vehicles between different altitudes and the usage of low octane fuel in high altitude regions. Thus the subjects of engine performance and engine knock, with particular attention to the effect of inlet pressure and mixture strength, is essential to the present study. Furthermore, in order to understand the effect of ethanol-gasoline blends on the response of engine to altitude, an overview of the relevant topics on alcohol-blend fuel is also necessary.

2.1 Altitude Effect on Engine Performance

2.1.1 Atmospheric Conditions and Engine Performance

The study of atmospheric conditions on engine performance is of interest on two counts. Firstly, this is a basis to understand how an engine should be tuned, under extreme atmospheric conditions, in order to maintain high performance. Secondly, in the field of engine testing, correction factors to adjust measured wide-open-throttle power to standard atmospheric conditions are essential to provide a more accurate basis for comparisons between engines.

Toyota Motor Co. has conducted a comprehensive study on the general effect of atmospheric conditions on the performance of a spark ignition engine^[5]. A Toyota 2R 4-cylinder gasoline engine of 1500 cc capacity was used in the tests. Inlet air pressure was controlled using a 4 in. (10 cm) valve to depress the pressure of air entering into a suction air surge tank. Exhaust gas was ejected by a vacuum pump through an exhaust surge tank. Pressure in the exhaust surge tank was controlled to the same level as the suction air by means of two in parallel 4 in. (10 cm) valves. Temperature and humidity conditions of the inlet

air were controlled by a specially designed air conditioner. It was observed that the effects of atmospheric pressure, suction air temperature, and humidity on engine performance are independent of one another. The effects of each factors could, therefore, be studied individually.

Experimental results showed that the change in engine performance under standard settings with atmospheric pressure and humidity is larger than that under optimum settings. This was attributed to the deviation in air-fuel ratio and/or spark timing, under standard settings, from the optimum values. Change in engine performance with suction air temperature under standard settings is almost the same as that under optimum settings, because standard settings always give practically optimum values. Maximum output air-fuel ratio and optimum spark timing remain unchanged even if atmospheric pressure and suction air temperature change, but both change with humidity.

With optimum settings, the performance of the engine under various atmospheric conditions can be related empirically by the following equations^[5] to that at standard conditions (101 kPa and 293 K):

$$E = (E_0 + E_{f0}) \times \frac{P_d}{P_0} \times \sqrt{\frac{T_0}{T}} - E_f$$

$$E_f = E_{f0} + E_{fp0} \times \left(\frac{P_d}{P_{d0}} \times \sqrt{\frac{T_0}{T}} - 1 \right)$$

$$bsfc = bsfc_0 \times \frac{P_d}{P_{d0}} \times \sqrt{\frac{T_0}{T}} \times \frac{E_0}{E}$$

$$\eta_v = \eta_{v0} \times \sqrt{\frac{T}{T_0}}$$

As barometric pressure at a given height varies from day to day altitude (h) is usually defined by the barometric pressure (P) according to the relation^[6]:

$$h = 19200 \times \log\left(\frac{101.3}{P}\right)$$

Thus a barometric pressure of 84.6 kPa is taken as 1500 m altitude. While there is a certain relationship between pressure and altitude, under the terrestrial altitude change, the change in air temperature is small and depends mainly on the climatic variations. Therefore, atmospheric air pressure is the dominant factor in the study of altitude effect in the automotive context.

2.1.2 Carburation

Carburation entails the supply to the engine with a mixture of fuel and air in proportions such that it can be easily ignited by the spark and leads to efficient combustion of the fuel constituents. Despite the complexity of the carburation process, the principle is governed by the Bernoulli's theorem. Flow rate of both air and fuel are directly related to the pressure drop across the venturi and sizes of the orifices. A simple carburettor, which represents the main metering system of a conventional carburettor, is shown in *Figure 2.1*.

In a carburetted engine, air is inducted into the cylinders by atmospheric pressure due to the pressure depression in the induction manifold and engine cylinders during the intake stroke. Fuel is fed through a jet into a venturi through which air flows with a local increase in speed. The fuel flow rate through the jet is determined by the pressure differential across it. Thus it is controlled by the volume flow rate of air in the venturi according to engine speed and load. As the volume flow rate of air increases, the pressure in the venturi falls and so more fuel is drawn off from the float chamber through the jet.

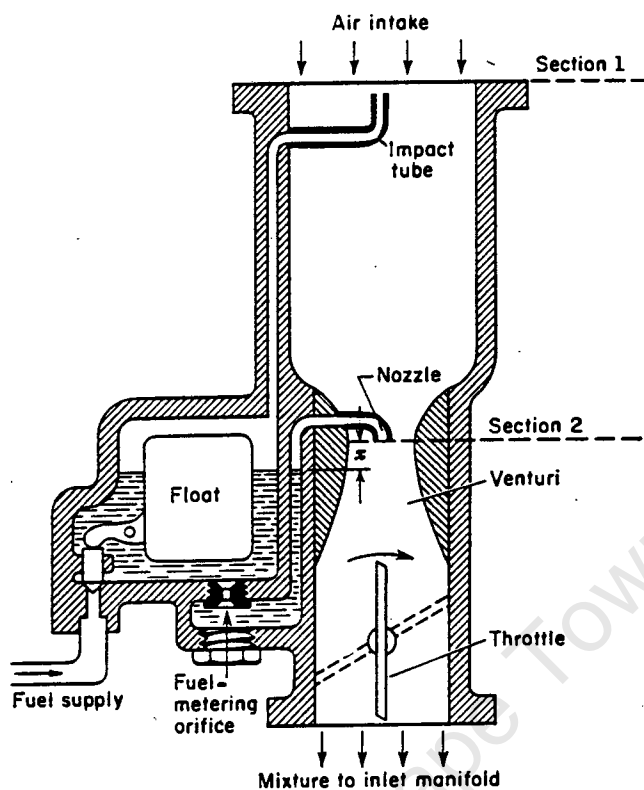


Figure 2.1 Layout of a simple carburettor^[7]

The derivation of the fuel/air ratio delivered by a simple carburettor can be found in most engine textbooks such as Taylor^[7] and Heywood^[8]. Basically, the mass flow rate of engine inlet air is proportional to air density while the corresponding fuel flow rate is proportional to the square root of air density. Thus, the fuel-air ratio (on a mass basis) delivered by a simple carburettor is inversely proportional to the square root of the inlet air density.

Engine tests by Toyota Motor Co.^[6] showed that the actual change of fuel flow rate with air density in a typical downdraught twin choke carburettor is larger than the theoretical one for a simple carburettor. The empirical relationship between air/fuel ratio and air density was found to be:

$$\frac{A/F}{(A/F)_0} = \left(\frac{\rho}{\rho_0} \right)^{3/8}$$

Bolt et al^[9] quantified the effect of altitude on carburation by enrichment E as defined below.

$$E = \frac{(F/A)_z}{(F/A)_0} - 1$$

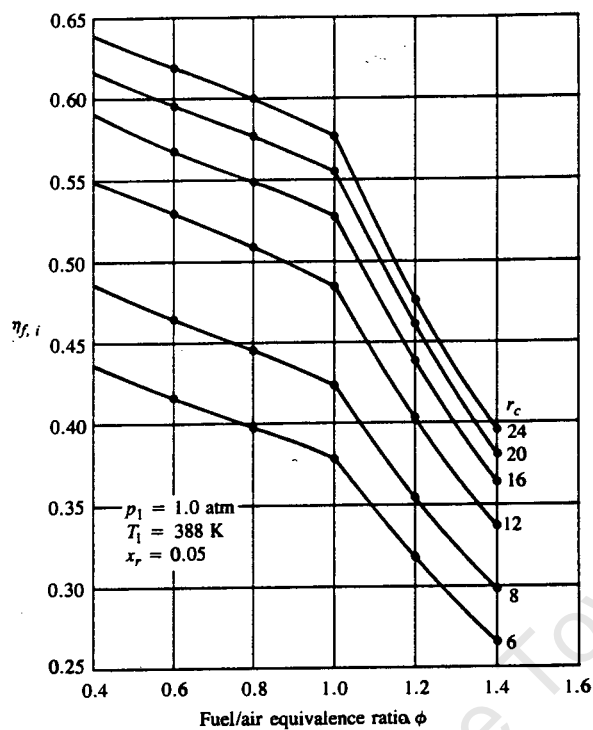
With tests on three different type of carburettors^[9], an empirical equation was established to correlate the effect of air density on enrichment. Such an equation, with conversion to SI unit and taken into account of the reference air density, is shown below.

$$E = 78.3 - 120.96 \times \left(\frac{\rho}{\rho_0}\right) + 42.64 \times \left(\frac{\rho}{\rho_0}\right)^2$$

2.1.3 Effect of Mixture Composition on Engine Performance

Mixture composition during combustion, which consists of carburetted fuel-air mixture and residual burned gas, is a critical parameter in determining the development of the combustion process and thus governing the engine's operating characteristics. Extensive results of constant-volume fuel-air cycle calculations have been the theoretical basis for understanding the effect of changes in mixture composition, in terms of equivalence ratio^[7,8]. Figures 2.2 a and b shows the fuel-air cycle results for indicated fuel conversion efficiency and mean effective pressure as a function of equivalence ratio. It can be seen that fuel conversion efficiency increases whilst the fuel/air equivalence ratio is below unity (i.e., the fuel-air mixture is leaner than stoichiometric). Heywood^[8] attributed this to the decrease in the burned gas temperature of lean mixture after combustion which decreases the burned gas specific heats and therefore effectively increases the value of γ , in the Otto efficiency equation $\eta_t = 1 - 1/r_c^{(\gamma-1)}$, over the expansion stroke. The efficiency increases because, for a given volume-expansion ratio, the burned gases expand through a larger temperature ratio prior to exhaust; therefore, per unit mass of fuel, the expansion stroke work is increased. On the other hand, as the equivalence ratio increases above unity, the efficiency

a)



b)

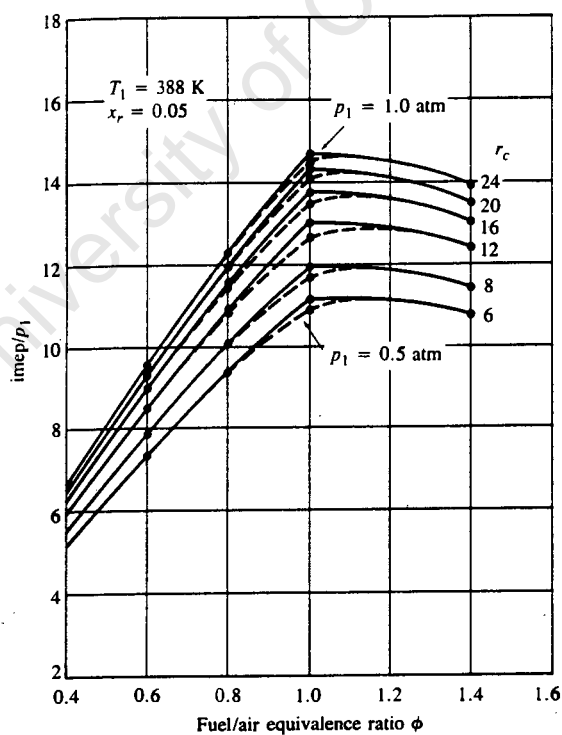


Figure 2.2

Fuel-air cycle results for
 a) indicated fuel conversion efficiency and
 b) indicated mean effective pressure as a
 function of equivalence ratio^[8]

decreases because lack of sufficient air for complete combustion of the fuel more than offsets the effect of decreasing burned gas temperatures, which decrease the mixture's specific heats. Theoretically, the indicated mean effective pressure is proportional to the product $\phi\eta_{fi}$. Consequently, a maximum imep is expected approximately at $\phi \approx 1.1$.

The theoretical fuel-air cycle calculation results are supported by engine data, as shown in Figure 2.3. The effects of ϕ on the indicated mean effective pressure (IMEP) and the indicated specific fuel consumption (ISFC) are evident. While standard carburetted engine could not operate at ϕ leaner than 0.85 without misfire due to cylinder-to-cylinder air/fuel ratio maldistribution, the use of a fuel vaporizing and a mixing tank essentially removes this maldistribution and extends the lean misfire limit. The observed decrease in η_{fi} with further decrease in ϕ was due to the increase in cycle-to-cycle pressure fluctuations and the total duration of the burning process, as the mixture becomes leaner^[8]. Both cyclic variations and longer burn duration directly decrease engine efficiency.

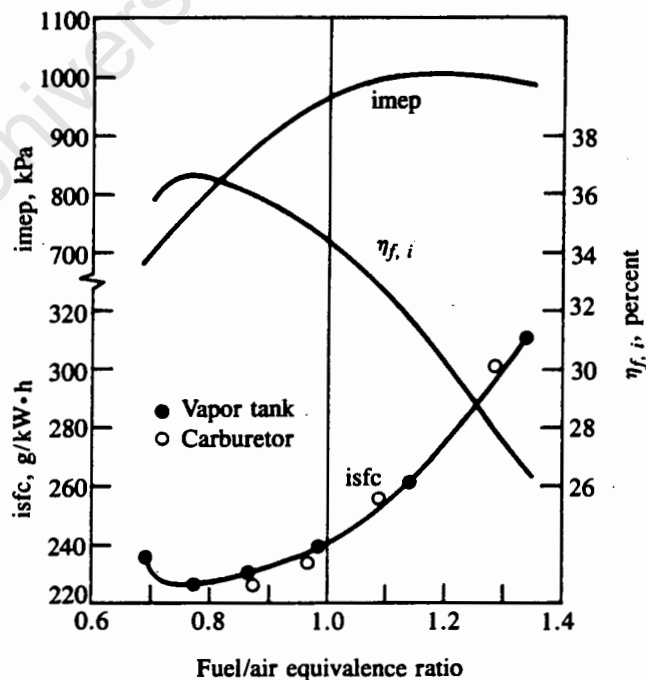


Figure 2.3 Effect of fuel/air equivalence ratio^[8]

The equivalence ratio is also an important parameter controlling spark-ignition engine emissions. The critical factors affecting emissions that are governed by the equivalence ratio, are the oxygen concentration and the temperature of the burned gases. Under lean of stoichiometric conditions, there is excess oxygen available for combustion. The maximum burned gas temperatures occur slightly rich of stoichiometric at the start of expansion stroke, and at the stoichiometric composition at the end of expansion and during the exhaust process^[8]. Figure 2.4 shows qualitatively the effect of ϕ on HC, CO and NO exhaust emissions.

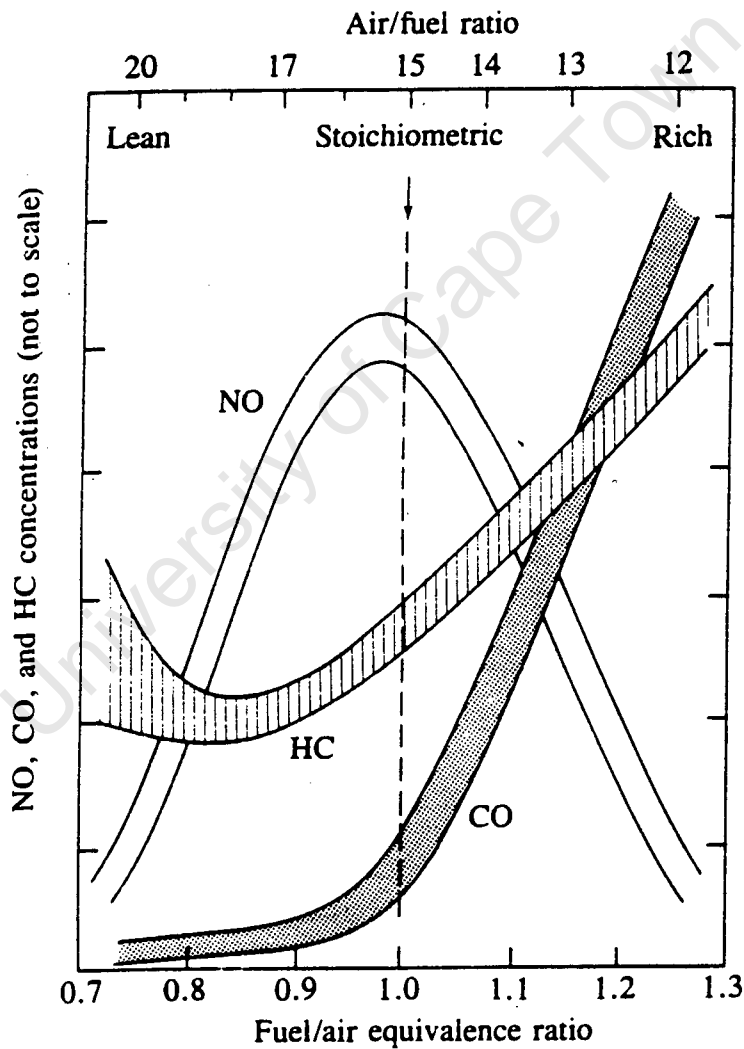


Figure 2.4 Variation of HC, CO and NO concentration in the exhaust of a conventional SI engine with equivalence ratio^[8]

2.2 Engine Knock in Spark Ignition Engine

2.2.1 The Phenomena of Engine Knock

Despite many years of research, the fundamental mechanisms causing and controlling knock in spark ignition engines are still not fully understood. While the formulation of a knock definition relies heavily on the proposed theory, Oppenheim^[10] has presented a generic definition to describe the engine knock phenomenon:

"Knock is an undesirable mode of combustion that originates spontaneously and sporadically in the engine, producing sharp pressure pulses associated with a vibratory movement of the change and the characteristic sound from which the phenomenon derives its name"

Various theories have been proposed that knock is associated with end gas autoignition, detonation, acceleration of the "normal" flame front, rapid combustion of partially oxidised gases behind the flame front, and a range of combinations of these effects^[11]. Most recent evidence, however, indicates that knock originates with the spontaneous autoignition of one or more local regions within the end-gas. A brief description of the autoignition theory will be given below. More exhaustive literatures on the subject of engine knock can be found in the textbooks of Ricardo^[12], Taylor^[7] and Heywood^[8].

According to the autoignition theory, knock is caused by the spontaneous combustion of the unburned mixture in the end-gas, near the combustion chamber wall, before the arrival of the turbulent flame front. Under normal combustion, the flame front propagates, from the point of initiation by the spark, in a fairly uniform manner across the combustion chamber. The mixture of fuel, air and residual gas ahead of the propagating turbulent flame front is compressed to higher temperature and pressure by the expanding burnt gases. Knock occurs when the unburnt mixture is subjected to a critical temperature and pressure condition that the fuel oxidation process - starting with the pre-flame chemistry and ending with the rapid energy release - occurs

spontaneously in parts or all of the end-gas region. Consequently, the rapid release of chemical energy in the end-gas creates a localized high pressure region within the combustion chamber and this pressure discontinuity leads to the propagation of supersonic shock waves across the combustion chamber. It is the impingement of the shock wave at the chamber wall, and resulting acoustic vibration of the chamber at its resonant frequency, that results in the characteristic metallic pinging sound of engine knock. The exact mechanism of how knock causes engine damage is not yet clarified. It is generally believed that the relaxing of the high pressure region disturbs the thermal boundary layer of stagnant gas that insulates the combustion chamber walls, increases the rate of heat transfer, and causes over heating of susceptible parts causing either local melting of the material or softening such that erosion ensues.

2.2.2 Influential Factors on Engine Knock

Generally, the occurrence of knock in an engine depends on the outcome of the race between the propagation of the turbulent flame front to consume the unburnt mixture, and the end-gas to autoignite in the combustion chamber. It is therefore apparent that by reducing the time for the normal flame travel across the chamber and lengthening the delay period of end-gas autoignition, the tendency of engine knock will be reduced, and vice versa.

The phenomenon of autoignition with compression rates similar to those occurring in the end-gas of an engine, has been extensively studied in a rapid-compression machine^[7,13]. Experimental data with various hydrocarbon fuels and over wide ranges of conditions invariably show that autoignition of the fuel-air mixture occurs at the end of an ignition-delay period. This ignition-delay period (τ) was found to depend not only on the nature of the fuel-air mixture but also on its pressure and temperature. An

empirical relations was developed^[13], which takes the form:

$$\tau = A \times P^{-n} \exp\left(\frac{B}{T}\right)$$

where A, n and B are fuel dependent constants. Any factor that lowers the end-gas pressure and temperature lengthens the ignition delay and therefore reduces the propensity of knock in an engine.

With respect to altitude, the propensity of engine knock changes as a result of the change in inlet air pressure and variation in equivalence ratio. A reduction in inlet air pressure decreases the flame speed but also reduces the compression pressure, and hence the pressures in the end-gas. It has been found that the latter effect, which increases the ignition-delay period of the end-gas, always dominates. As a result, a decrease in knock tendency is expected with lower inlet air pressure. Change in equivalence ratio also imposes a counteracting effect on knock tendency. While the length of the ignition delay for ordinary fuels is minimum at the best power equivalence ratio ($\phi \approx 1.1$), the flame speed is at its maximum. Experiments showed that the former is a dominating factor. Thus maximum tendency to knock occurs at about the best power equivalence ratio. The influence of other engine operating parameters on knock tendency is summarized in Table 2.1.

The effect of fuel octane number, inlet air temperature and spark timing on engine knock were established experimentally by Haghgoie^[14]. A dual sample rate technique was developed and applied to measure in-cylinder pressure and its oscillation due to autoignition in a Ricardo Hydra single cylinder engine. For a fuel with given octane number, the increase in inlet temperature results in retarded knock-limited spark timing. The spark timing range in which the transition between no knock and 100 percent knock was found to be about 10 crank angle degrees, regardless of the octane number of the fuel and inlet air temperature. The cause of this spread was attributed to the cycle-to-cycle variations of the mixture stratification, in-cylinder fluid motion and heat transfer. Haghgoie argued that if there were no cyclic variations in the engine operation, the transition region between no knock and 100 percent knock would

have been very small. A linear relationship was observed between the crank angle of the knock occurrence to TDC, which is independent of the inlet air temperature and fuel octane number, and the spark timing. Analysis of cylinder pressure in terms of power spectral density suggested that the knock intensity stays almost constant up to the point where almost 100 percent of the cycles are knocking. This trend is independent of inlet air temperature and fuel octane number. Haghgoie interpreted this to mean that knock consists of single-site autoignition for operations with less than 95 percent knocking cycles and multi-site autoignition for operation with 100 percent knocking cycles.

Table 2.1 Summary of factors affecting knock tendency

Factor	Effect	Pro-knock	Anti-knock
Compression ratio	Increase	✓	
Inlet air temperature	Increase	✓	
Inlet air pressure	Decrease		✓
Equivalence Ratio	lean		✓
	Slightly rich	✓	
	Over rich		✓
Engine speed	Increase		✓
Ignition timing	Advance	✓	
Cooling water temperature	Increase	✓	

2.2.3 Anti-knock Quality of Fuel and Engine Requirement

The anti-knock quality of an automotive gasoline is of prime importance in preventing the propensity of knock in an engine. It is essential to use a standard method to assess the knocking characteristics of engine fuel. However, knock depends on complex physical and chemical phenomena which are highly interrelated with engine design and engine operating conditions. It has not been possible to characterize completely the antiknock performance of engine fuel with any single measurement^[15].

A comprehensive study to relate the anti-knock performance of commercial and primary reference fuels to a wide range of atmospheric conditions was conducted by Potter et al^[16]. Based on nine test cars of different makes, Potter et al explored the effects of atmospheric pressure, temperature and humidity on the knock ratings of commercial fuels and on their ability to satisfy vehicles. The Modified Union-town Technique was used for all of the fuel ratings and engine requirement assessment. In this technique a fuel is rated in terms of the degree of spark advance that the fuel will tolerate before trace knock occurs. The greater the number of degrees of spark advance, termed knock-limited spark advance (KLSA), that a fuel will tolerate, the higher its antiknock quality.

Table 2.2 Effect of atmospheric conditions on KLSA, fuel octane rating and engine octane requirement^[16]

Conditions	KLSA	Fuel Octane Rating	Engine Octane Requirement
Pressure decrease from 30 in. Hg to 27 in. Hg (103.6 kPa to 93.3 kPa)	increase by 8.5° (+0.83° per kPa)	decrease by 2.5 ON (0.24 ON per kPa)	decrease by 7 ON (0.7 ON per kPa)
Temperature increase from 30°F to 90°F (-1.1°C to 32.2°C)	decrease by 3° (-0.09° per °C)	increase by 1.1 ON (0.03 ON per °C)	increase by 3.6 ON (0.11 ON per °C)
Humidity increase from 30 to 130 grain water/lb air (4.29 to 18.57 g water/kg air)	increase by 4° (0.28° per g water/kg air)	decrease by 1 ON (-0.07 ON per g water/kg air)	decrease by 3.9 ON (-0.27 ON per g water/kg air)

Potter et al found that both the fuel rating of commercial fuels and the engine octane requirement based on primary reference fuels changed with atmospheric conditions. The average effects are summarized in Table 2.2. The approximate changes in parameters with respect to unit increase in conditions are calculated and shown in brackets. It is important to realize

that atmospheric conditions have a major effect on the ability of commercial fuels to satisfy engine octane requirement. While the engine octane requirement decreases with the pressure reduction of 10 kPa (equivalent to an 900 m increase in altitude) by 7 octane numbers, the rating of commercial fuel decrease by 2.5 octane numbers. Therefore there is only an average of 4.5 (7 - 2.5) octane numbers gain in the anti-knock quality of the fuels relative to engine requirement with respect to the 900 m altitude elevation.

Nowadays, the anti-knock rating based on the octane scale on a CFR-engine adopted by the ASTM is widely used. The octane number is defined as the percentage of iso-octane (2,2,4-trimethyl pentane) in a blend with n-heptane that gives the same resistance to knock as the test fuel under standard conditions in the CFR-engine. Two different methods are used for determining the anti-knock rating of gasolines. The Research Octane Number (RON) is determined under mild operating conditions at a moderate inlet mixture temperature and a low engine speed. The Motor Octane Number (MON) is determined under more severe operating conditions at higher inlet mixture temperature and a higher engine speed than those employed in the Research method. The test conditions for the two test methods are summarized in Table 2.3.

Table 2.3 Operating conditions for research and motor methods of octane rating

	Research Method	Motor Method
ASTM designation	D2699	D2700
Engine speed	600 rpm	900 rpm
Inlet pressure	Atmospheric	
Mixture temperature	52°C	149°C
Humidity	0.0036-0.0072 kg/kg dry air	
Coolant temperature	100°C	
Air/fuel ratio	Adjusted for maximum knock	
Spark Advance	13 °BTDC (constant)	19-26 °BTDC (varies with compression ratio)

The extensive data-base from the annual CRC octane number requirement survey showed that the anti-knock performance of a gasoline in some vehicles may correlate best with RON, while in others it may correlate best with MON^[3]. In general, RON indicates knock resistance of gasoline in engines under wide-open-throttle (WOT) and low-to-medium engine speeds. On the other hand, MON indicates the knock resistance under WOT and high engine speeds and also part-throttle road-load conditions. The difference in RON and MON represents the sensitivity of the fuel to changes in the severity of engine operating conditions in terms of anti-knock performance. *Figure 2.5* shows the significance of fuel sensitivity to knock response of an engine. Depending on the fuel sensitivity and shape of the spark-advance curve, the knock region may occur at low, medium, or high speed.

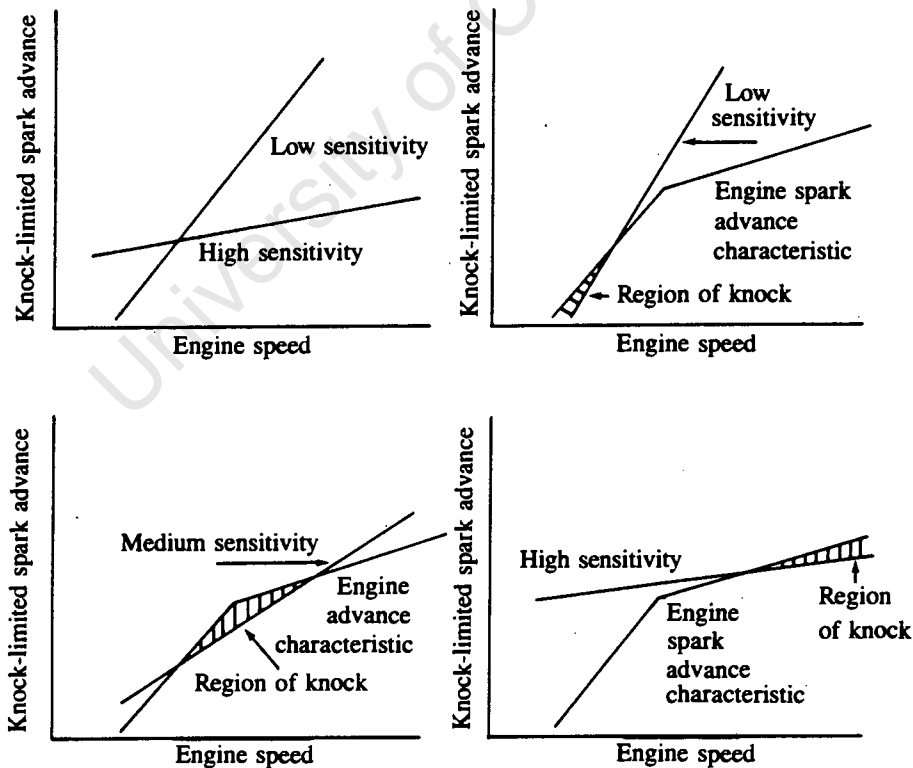


Figure 2.5 Engine knock response to fuels of different sensitivity^[8]

2.2.4 Altitude Octane Number Requirement Surveys

Initial observations on the reduction of octane number requirement at high altitude were made in the 1940s^[1]. Since then research has been conducted by various research groups. Knowledge concerning the magnitude of altitude effects on octane number requirement of passenger cars is of considerable interest to the petroleum companies. In 1949, Ethyl group^[17] conducted tests on five cars with both primary and full-boiling range reference fuels. An average decrease of 2.4 RON requirement per 1000 ft (300 m) was observed. Similar tests were accomplished through a joint program by the Ethyl group and Chevron Research Co. in 1965^[18]. Eight cars were tested and found to have an average of 1.5 RON requirement decrease per 1000 ft (300 m). These studies showed that changes in engine design over years, which alter the engine-fuel relationships, affect the octane number requirement at high altitude.

It was not until 1971 that the Coordinating Research Council (CRC) initiated the representative high-altitude octane number requirements tests with 1967-1972 car models^[19]. This significant altitude programme became the basis of the ASTM D439 (now D4814) automotive gasoline specifications^[3]. These specifications allow gasolines sold in high-altitude areas of America to decrease 1.0 to 1.5 AKI (defined as $(RON+MON)/2$) per 1000 ft (300 m), up to a maximum of 4.5 AKI lower than those sold at low altitudes.

The reduction of octane number requirement was understood to be due to the effect of changing barometric pressure on induction and ignition management system function, via the change in mixture strength and spark timing with altitude^[2,20,21]. In earlier cars, the spark advance and carburettor enrichment were largely controlled by manifold vacuum. A manifold vacuum decrease indicates a higher load on the engine, which resulted in less spark advance and a richer mixture to avoid knocking. However, a lower manifold vacuum occurs at higher altitudes under the same engine loads and hence demands lower octane requirement. The effect of altitude on vacuum spark advance is shown in Figure 2.6.

From 1981, certain model cars in the US market have been equipped with electronic systems for controlling air-fuel mixture and spark timing, and some even with sophisticated altitude compensating systems^[2]. With these engine management systems, air-fuel mixture at part throttle is controlled near stoichiometric at any altitude and spark timing may be advanced as a result of barometric pressure decreases with altitude. The decrease in octane number requirement with altitude for these cars was expected not to be as much as that for previous model cars. In 1981, CRC conducted another altitude programme^[2] to determine the effect of altitude on octane number requirement, particularly for those with electronic control of air-fuel mixture and spark timing. Results showed that the 1981 model cars in America had an average reduction of 1.7 RON (or 1.3 AKI) per 1000 ft (300 m) while those with barometrically compensated spark timing and/or feedback air-fuel control showed only an average decrease of 0.6 RON (or 0.5 AKI) per 1000 ft (300 m).

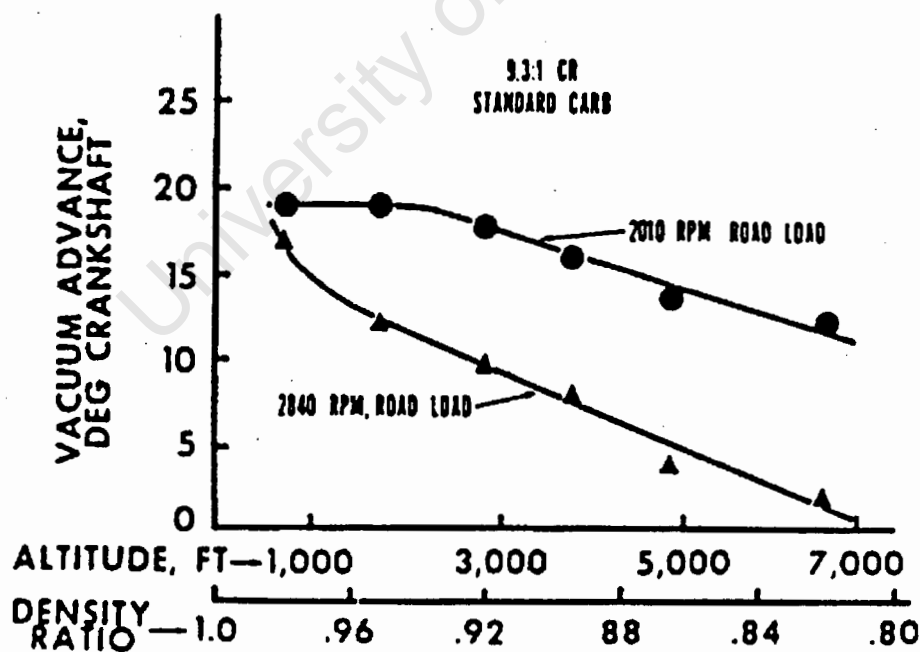


Figure 2.6 Effect of altitude on vacuum spark advance^[22]

A recent survey was conducted by Amoco Oil Co.^[20] on twelve 1984-1986 US model cars and light trucks. All the test cars were equipped with closed loop fuel control systems which sense exhaust oxygen level and maintain part-load air-fuel mixtures at stoichiometric levels. Tests were carried out with full boiling range unleaded and full boiling range high sensitivity unleaded gasolines, and with altitude up to 7000 ft (2100 m). Only an average of 0.2 AKI reduction per 1000 ft (300 m) was observed. A similar survey was conducted by Petro-Canada^[21] on a fleet of seventeen vehicles with six models being equivalent to those used by Amoco. An average of 0.5 AKI reduction per 1000 ft (300 m) increase was observed. Petro-Canada postulated that the discrepancy between their results and that reported by Amoco could be due to difference in test procedure, vehicle selection and normal random variation in control system function within the equivalent models. It was concluded that a study using a considerably larger fleet size is required to clarified the results.

In 1990, a preliminary investigation on high-altitude octane requirement was conducted in South Africa^[23]. Some cars were found to be incapable of operating knock-free with the current highveld premium grade petrol (84 MON). Owing to an insufficient database, it was concluded that the quality of Highveld premium grade should not be reduced and further test should be carried out on a larger sample of cars to determine the exact fuel quality requirements of the car park. Currently, compared with the American specification, an equivalent reduction of 0.8 AKI per 300 m is adopted in this country.

2.3 General Consideration in the Use of Alcohol-Blended Fuel

Consideration of the use of alcohols, also known as oxygenates, as an automotive fuel additive is almost as old as the internal combustion engine itself. Among the various alcohols, methanol and ethanol are most popularly used in alcohol-gasoline blends. Extensive research^[24,25] has been carried out in evaluation of the impacts of alcohol-blended fuel on various aspects of engine

performance. The use of alcohol as a component for blending with gasoline is attractive in many ways: a) as a potential additional energy resources for automotive fuel; b) as a octane booster for base gasoline; c) reduce exhaust HC and CO emissions. On the other hand, there are still a lot of concerns on the use of oxygenate-blends because they exhibit a) impaired vehicle driveability; b) increased evaporative emissions; c) increased exhaust emissions of NO_x; d) water tolerance and phase separation problem and e) reduced volumetric fuel economy. However, the interest of this thesis is on the consequence of using an alcohol-blended fuel with changes in altitude, rather than the study of oxygenate-blends as alternative fuels, the following discussion will be limited to the mixture leaning effect and anti-knock quality of oxygenated gasolines.

2.3.1 Mixture Leaning Effect of Alcohol

The stoichiometric air-fuel ratio $(A/F)_s$ for burning a hydrocarbon fuel consisting of carbon, hydrogen and oxygen can be expressed by the equation:

$$(A/F)_s = 34.56 \times \left(\frac{c}{3} + h - \frac{o}{8} \right)$$

where the symbols c, h and o represent the quantities of carbon, hydrogen and oxygen contained in one kilogram of fuel. For straight gasoline on the market, the value of o is zero and the ratio of c to h is about 6.4 to 1^[8]. Thus, from the equation, $(A/F)_s$ for straight gasoline is about 14.6. Oxygenates have very different stoichiometric air-fuel ratio from gasoline. For instance, ethanol (C₂H₆O) has a ratio of c to h to o of 12:3:8 and so $(A/F)_s$ is equal to 9. Blending oxygenates to gasoline will not change the physical properties of the blend significantly. Consequently, fuel metering systems without oxygen sensor feedback control will meter both straight gasoline and alcohol-blend at approximately the same air-fuel ratio. However using an alcohol-blend, with a lower stoichiometric air-fuel ratio, results in a decrease in fuel-air equivalence ratio (ϕ) and causes an effective change in fuel system calibration.

As discussed above, ϕ has a direct influence on engine performance and exhaust emissions. It is expected that the mixture leaning effect of blending oxygenates to gasoline should have an influence on engine performance and exhaust emissions.

Brinkman et al^[26] explored how alcohol addition to gasoline affects exhaust emissions. Various engine tests were conducted in which stoichiometry was varied not only by varying the concentration and type of alcohol blended with gasoline but also by modifying the carburettor to obtain air-fuel ratios nominally 6 and 15 percent richer than that of the production carburettor. The modifications were selected to compensate for the leaning effect which would be expected from the addition of alcohols. The study showed that blending gasoline with alcohol generally reduced HC and CO emissions but increased NO_x emissions. This was attributed to the leaning of the intake charge. It was concluded that the mixture leaning effect of alcohol blending essentially does the same thing as is done with straight gasoline by mechanical carburettor adjustment, namely, leaning out the mixture to a lower equivalence ratio.

The effect of blending different oxygenates to a synthetic hydrocarbon base stock gasoline on exhaust emissions has been extensively studied by Sasol Oil R&D^[27]. Engine test were carried out in a Ricardo Hydra MK III, single cylinder engine. It was found that different oxygenates affect exhaust emissions in a similar manner. The magnitude of emission reductions depend only on the fuel oxygen content. Both HC and CO emissions decreased with increasing oxygen content.

The use of 10 percent ethanol blend as a strategy for emission reduction at high altitude has been proposed in the United State by the Colorado Department of Health^[28,29] and the Environmental Protection Agency^[30]. Analysis of the separate low and high altitude emission data-bases indicated that, under different operating points at altitudes, the blend had essentially the same effects on the reduction of HC and CO emissions on a percent basis, while the reductions on an absolute basis were generally higher at high altitude^[30].

2.3.2 Anti-knock Quality of Alcohol-Blend Fuels

As mentioned above, one of the most attractive features of blending oxygenates with gasolines is the ability to boost the octane number of the base gasoline. The octane-boosting quality of alcohols, for use as blending components, has been intensively analysed^[24,25]. The octane boosting ability is commonly expressed and compared in terms of the blending octane value (BOV) which is defined by:

$$BOV = \frac{(ON_{blend} - ON_{base} \times (1 - x))}{x}$$

where x is the volume fraction of alcohol in the blend. The BOV was found to be strongly dependent on the octane number and composition of the base stock. Ethanol as a pure component has an RON of about 106, while with 10 volume percent ethanol in unleaded gasoline (as the Nebraska GASOHOL) its Research BOV was found to be 134^[31].

Figure 2.7 shows the increase in research and motor octane number caused by adding 10 percent alcohol to various base gasolines. As the octane number (either RON or MON) of the base gasoline increases, the octane increase due to alcohol becomes progressively smaller. Generally, blending alcohols into gasolines has a greater octane boosting effect on RON than MON, and thus increases the fuel sensitivity. The effect of adding ethanol, in various volume percentages, on the increase in octane numbers is shown in Figure 2.8. The increase in fuel sensitivity suggests that blends with high alcohol concentration would be no better in satisfying car octane requirement on the road than low alcohol concentration blends^[26].

While alcohols have an octane boosting properties, many researchers have realized that the present ASTM-specified octane rating method of either RON or MON for gasolines is not an adequate measure of the anti-knock quality of oxygenate fuels.

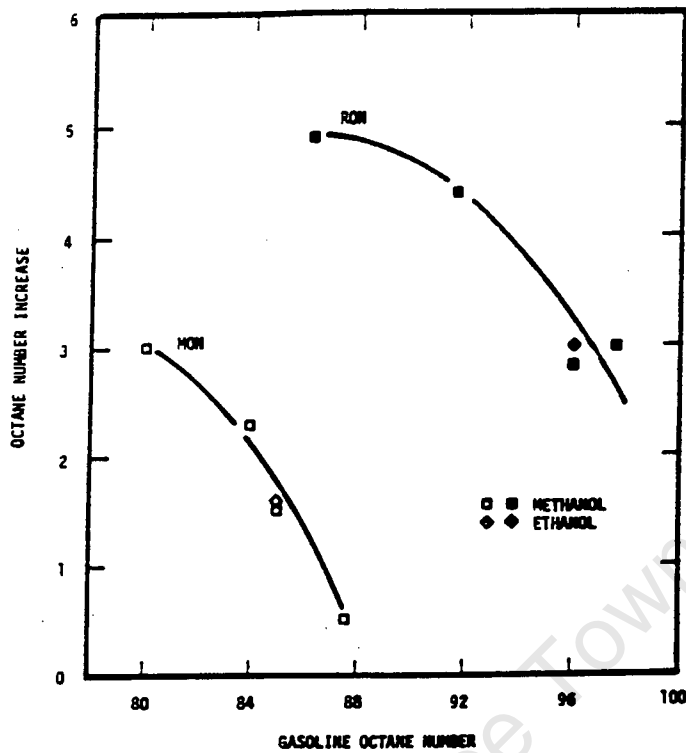


Figure 2.7 Increase in RON and MON by adding 10% alcohol to various gasolines^[26]

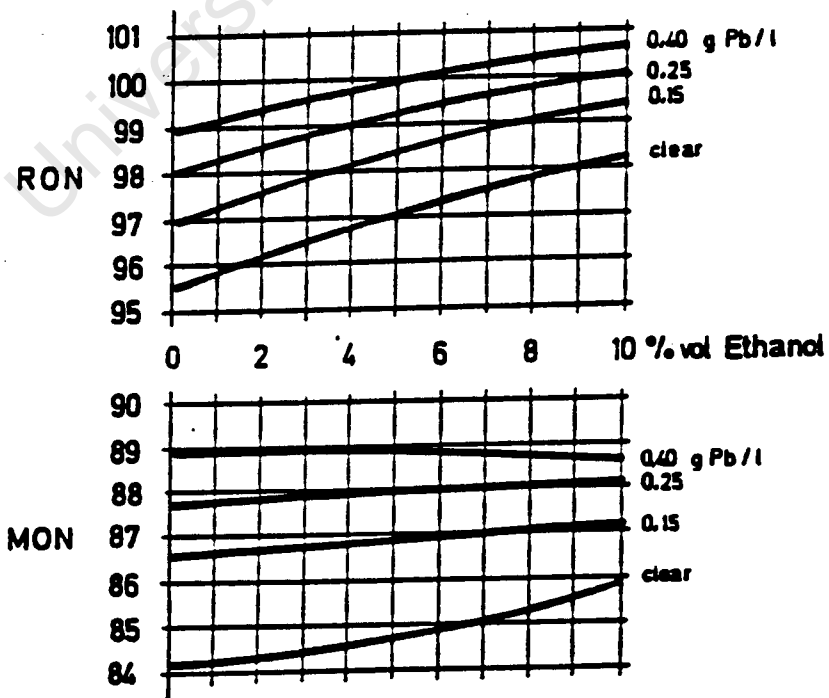


Figure 2.8 Laboratory octane numbers of ethanol-gasoline blends^[33]

Brinkman et al^[26] studied the effects of alcohol on octane number by looking at the road octane number of methanol-gasoline blends of various concentrations. Figure 2.9 summarizes the experimental results. While both the RON and MON were increased, at speed greater than 2800 rpm, adding more than 5 percent methanol reduced the road octane number of the blend. This reduction was found to be severe enough at speed higher than 3600 rpm to decrease the road octane of the blend to values lower than those of the base gasoline. Brinkman et al explained this anomaly by considering that the test engine had a maximum octane requirement at an equivalence ratio on the rich side of stoichiometric ($\phi \approx 1.1$), and decreases at either richer or leaner ratios. With base gasoline, the operating equivalence ratio is too rich for the octane requirement to be maximum. Adding methanol to the gasoline decreased the equivalence ratio towards values closer to 1.1 where octane requirement is maximum. Brinkman et al concluded that methanol had two counteracting effects: it increased engine octane requirement by leaning the intake charge, whereas it increased fuel octane rating by improving knock resistance. This counteraction, however, does not occur in the ASTM octane tests because air-fuel ratio is adjusted to obtain maximum knock for each fuel tested.

The effect of mixture strength on knock was investigated by Radwan^[32], with various ethanol-gasoline blends ranging from 10 to 70 percent ethanol by volume on a Ricardo E6 variable compression engine. By measuring the knock-limited compression ratio, for each blend at different mixture strength, the influence of mixture strength on the knock tendency was experimentally established. With straight gasoline, the greatest tendency to knock occurred at a mixture slightly richer than the stoichiometric. Increased concentration of ethanol in the blend shifted that point to a richer ratio. It was observed that lean mixtures, particularly with higher concentrations of ethanol significantly enhanced knock resistance.

Marhold^[33] studied the influence of different oxygenates in commercial leaded and unleaded gasolines on octane requirement of a fleet of European cars. It was found that all test cars

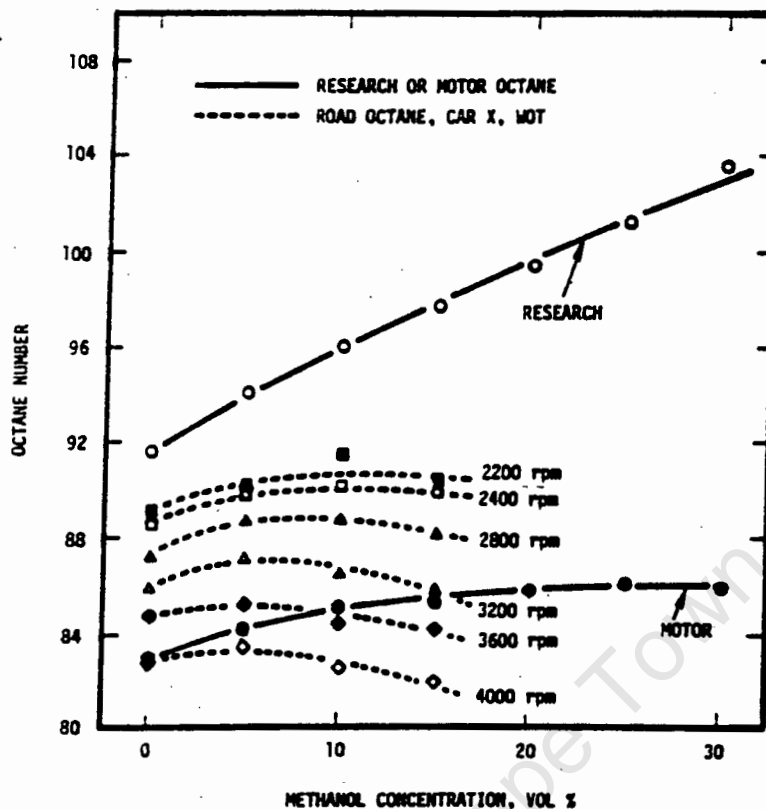


Figure 2.9 Effect of adding methanol to gasoline on research, motor and road octane numbers^[26]

required a higher Octane number with the oxygenate-blends than with straight gasolines in order to provide the same knock protection. The increase in octane number requirement with the oxygenate-blends was more significant at high speeds. To study the octane number requirement with alcohol-blends and the effect of lead concentration in the fuels, Marhold performed constant speed test at 6500 rpm with blends of ethanol and methanol. All the blends had the same Research Octane Number of 98. The ethanol-blends were found to have a lower anti-knock quality, in terms of Road Octane Number, than methanol-blends. It was found that there were greater reduction in Road Octane Number with higher lead concentrations in the fuels. Similar trends of increasing vehicle octane requirement when using gasoline/ethanol blends were reported by Histon and Roles^[34].

Concerning the misleading result of using the ASTM octane rating as a measure of anti-knock quality of alcohol-blend fuels,

Westerholm and Nylund^[35] developed a new measurement method. A slightly modified 2 litre, port injected, four cylinder SAAB H-series engine was chosen as the test engine. The knock resistance of the fuel is measured in terms of the knock-limited spark advance of an engine. To be able to define the knock limit non-intrusively, all measurements were made in a transient mode, in which the spark advance was increased linearly by 10 crankangle degrees over a duration of 80 subsequent engine cycles. Cylinder pressure traces were acquired simultaneously. Thus both normal and knocking engine cycles were recorded. All the measured cycles were categorized according to the spark timing to the nearest crankangle degree. Combustion cycles with knock were identified with the aid of FFT autospectrum analysis of the cylinder pressure traces. The KLSA was defined as the groups in which 33 percent or more working cycles were knocking. Westerholm and Nylund argued that the method provides a better measurement of the knock behaviour of fuel blends containing oxygenates. The SAAB engine showed a greater increase of the octane number (derived from the primary reference fuel) on moderate engine speeds than on lower speeds. However, the increase of the real knock resistance of the gasoline-ethanol blends in terms of KLSA was equal over the whole tested speed range.

CHAPTER 3

EXPERIMENTAL METHODS

3.1 Strategy of Investigation

3.1.1 Basic Considerations

As has been discussed, it is understood that the impact of altitude on SI engines is primarily caused by the variation in compression pressure and change in air/fuel ratio. The latter effect is believed to be less pronounced if an engine is fitted with an altitude compensated carburettor or using a fully management fuel injection system. Such an engine is, therefore, expected to be less affected by altitude changes.

In South Africa the majority of the vehicle population are still equipped with carburettors, without any provision for compensation for the altitude changes. Therefore, to address the problems of altitude variations in the South African context, carburetted engines are most appropriate for investigation. Moreover, it is desired to investigate the effect of carburation to engine response with altitude changes. Thus, experiments should be carried out on the same engine with and without compensation provision for air/fuel ratio change with altitudes.

This project was instigated in order to obtain a more comprehensive understanding of the impacts of altitude on vehicle engine. Owing to the time and budget constraints, tests could only be carried out with a single engine. This engine was one found in one of the popular locally mass-produced vehicles.

3.1.2 Engine and Test Fuels

A Toyota 4A-F four in-line cylinder engine was selected for the altitude experiments, since it was one of the four test engines used in a previous altitude program⁽⁴⁾. Results from the tests suggested that this engine is more susceptible to engine knock under the influence of altitude change. Engine specifications are given in Appendix A.

Engine tests were carried out with straight gasoline as well as a 10% alcohol-blended gasoline. Coastal 93 octane (regular) pump gasoline was chosen as the base fuel. Although this fuel has the same specified RON as the Reef 93 (premium) pump gasoline, they have different origins. The coastal fuel is crude oil derived while the Reef fuel is produced by SASOL from coal. In the past the Reef fuels were blended with 8% ethanol and 2% higher alcohol, which are by-products of the SASOL oil-from-coal process. However, at the time of engine test, SASOL ethanol was being exported and therefore was no longer blended with gasoline. A previous study^[36] showed that blending 10% ethanol by volume with 93 RON blend stock is equivalent to 97 RON in terms of knock resistance. To make up a 10% alcohol blend with RON close to 93, the blend was obtained by split-blending 10% by volume of ethanol into a blend stock, in equal volume of coastal 93 and reef 87 pump fuel. The resulting ethanol blend has a RON of 95.3, while the base fuel has a RON of 92.7. Properties of the test fuels are given in Appendix B.

3.1.3 Engine Tests

In order to evaluate the altitude effect under practical conditions, three different carburation settings were examined, namely:

- 1) Sea-level carburation
- 2) Highveld carburation
- 3) Altitude-compensation

Each carburation setting is designed to address different "real-life" situations. The sea-level carburation refers to fitting the original carburettor with the orifice jet size as specified by the manufacturer. The test is to simulate a situation when a car is tuned under coastal conditions and driven up to the Highveld. The practical situation of having a car tuned in the Highveld areas and driven down to the coast was evaluated by the Highveld carburation test. Although, no specifications on the carburettor jet sizes, for the Highveld areas, are given by the engine manufacturer, it is a common practice to reduce the main

jet by 1 unit point for every 300 m of altitude. In this study an "ideal" case is adopted where the engine was fitted with a carburettor designed for operation in the Highveld. In other words, the Highveld carburation is adjusted so as to give the same air/fuel ratios as operating under sea-level condition. The altitude-compensation test was designed to simulate an engine with a closed-loop fuel management system, where the effect of altitude on carburation system is eliminated. This was accomplished by maintaining the air/fuel ratio, at various altitudes, at the same sea-level values at corresponding operation points. Hence the sole effect of variation in inlet pressure on engine can be determined.

For each carburation setting, engine tests were performed at pressures equivalent to altitudes of 0 m (101.3 kPa), 400 m (96.7 kPa), 800 m (92.1 kPa) and 1200 m (87.5 kPa). At each altitude, the engine was tested at four different speeds from 1500 rpm to 4500 rpm in steps of 1000 rpm. All test were carried out at wide-open throttle (WOT). In order to eliminate other factors affecting engine knock, the inlet air temperature was maintained at 50 °C, and coolant water and oil temperatures were controlled at 95 °C and 85 °C respectively.

3.2 Experimental Set-up

3.2.1 Altitude Test Cell and Apparatus

The experiments were carried out in the high altitude test cell designed by Mearns^[4] in the Energy Research Institute. The schematic layout of the altitude cell is shown in *Figure 3.1*. A two-stage backward curved centrifugal fan, driven at 4400 rpm by a 45 kW electric motor, is used to provide a maximum pressure depression down to 84.5 kPa in the test cell. The pressure depression in the test cell is controlled by variation in the area of a shutter baffle opening. Thus atmospheric pressure conditions at any altitude up to 1500 m can be simulated. The test cell pressure was measured by an integrated pressure sensor KP100A. Calibration of the pressure sensor was carried out by a Druck type DP602 multichannel pressure indicator.

The test cell is equipped with a 300 bhp (224 kW) Heenan & Froude eddy current dynamometer with torque and speed measurement and control capability. The accuracy of the speed indicator was verified by a Lutron type DT2234A optical digital tachometer, which is accurate to ± 1 rpm up to 5000 rpm. Torque was measured via an HBM load cell connected to a linkage which allows for direction reversal of the H&F dynamometer.

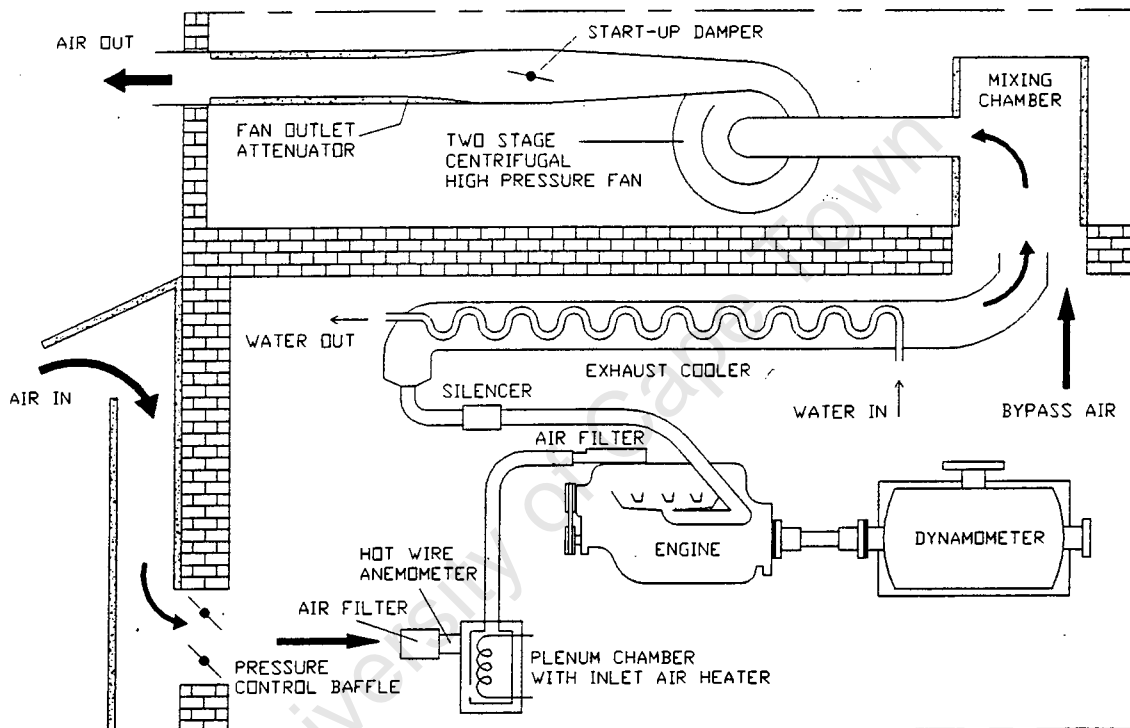


Figure 3.1 Schematic layout of the altitude simulation test cell

The engine installation on the test bed was kept as close as possible to that encountered with the engine installed in a vehicle. The original air intake system, including air filter and associated ducting, was used. The air intake was connected via a 120 mm diameter flexible tube to a plenum chamber containing electric heaters. This enabled a constant air intake temperature of 50 °C to be maintained throughout the tests.

Inlet air temperature was measured upstream of the air filter. Oil temperature was measured at the outlet of the oil filter. Top hose water temperature was measured on the radiator side of the thermostat. Exhaust gas temperature was measured about 50 cm from the exhaust manifold flange. All temperatures were measured by k-type thermocouple with the corresponding amplifiers and digital displays.

Initially, inlet air flow rate was measured using orifice plates in accordance with BS1042 Part 1. Surprisingly, it was found that the flow measurement set-up increased the torque output at speeds lower than 3000 rpm by some 3 to 5 percent, while having no effect at high speeds. The increase in torque output was associated with raise in inlet manifold pressure. This "supercharging" effect was believed to be due to pressure wave action in the inlet pipe, which compressed the inlet air. It was anticipated that this "pressure wave supercharging" action would vary with inlet air pressure and consequently the flow measurement set-up was deemed to be inappropriate for this experiment. Attempts were made to use a BOSCH hot wire anemometer for air flow measurement. The hot wire anemometer was originally installed in a commercial engine and had been used for air flow measurement in a single cylinder engine. The hot wire anemometer was calibrated by orifice plates, with air flows generated by two vacuum pumps connected in parallel to a throttle valve at the outlet.

The mean fuel consumption was measured by using a PC computer which timed the flow of a mass of fuel from a flask located on a load cell. Inlet and exhaust manifold pressure were measured by integrated pressure sensors. A non-dispersive infra-red (NDIR) gas analyzer was used to measure carbon monoxide and carbon dioxide concentration in the exhaust gas. The sample line includes a heated 10 micron filter, a chiller to remove moisture, and a 5 micron borosilicate filter to remove particulates before entering the gas analyzer. Calibration of the instrument was carried out by span gasses of 0.1 percentage point accuracy.

In order to detect the onset of trace knock and determine the knock limited spark advance, a Kistler 6121 piezo-electric

pressure transducer was fitted in the No. 1 cylinder of the engine, with the diaphragm of the transducer flush with the combustion chamber wall. A PCB type F462A charge amplifier was used to convert the transducer signal to a voltage suitable for recording. No calibration was done and an arbitrary zero level of 0 bar was used, as detailed combustion analyses were not required. The pressure diagram was monitored on an oscilloscope screen during the tests. To vary ignition timing, the vacuum advance was disconnected and the distributor was loosened slightly and coupled to a RS type 318-711 stepping linear actuator via a cable wire. An optical TDC and crank angle degree marker were mounted on the crank shaft pulley. An inductive pickup on the spark plug HT lead was used in conjunction with an electronic triggering device to provide an electronic pulse at spark plug discharge. The real-time spark timing of the engine was measured and displayed on a spark advance display unit designed and built in the Energy Research Institute.

The cylinder pressure traces, spark and TDC signals were all recorded simultaneously using an ISC-16 computerscope data acquisition system supplied by RC Electronics. The system comprises a hardware card which is installed in one of the expansion slots of an IBM PC-XT computer, as well as driver software. Up to 16 input channels may be multiplexed to a 12 bit analogue to digital converter capable of sampling at a maximum rate of 1 MHz. An input range of -10 to +10 volts is allowed and the card has a 64 kB on-board memory buffer, allowing up to 65536 samples to be captured. The data can be saved on magnetic disk for subsequent analysis.

The spark and TDC signals were superimposed and the signal recorded on one channel of the A/D system. The pressure signal was recorded on a separate channel. Data sampling was triggered by the crank angle signals. With the crank angle degree marker set to send out 1800 symmetrical pulses per revolution, a sampling rate of 0.2 crankangle degree interval was achieved. The data were temporarily stored on the hard disk of the host computer during the tests, and were subsequently transferred to floppy diskettes for permanent storage and later analysis.

3.2.2 Adjustment of Air/Fuel Ratio

The Toyota Engine is equipped with a downdraught twin barrel carburettor (the schematic layout is shown in Appendix A), which has no provision for run-time adjustment of the air/fuel ratio. The required air/fuel ratio was accomplished by varying the area of the primary main jet of the carburettor with a tapered needle. The size of the secondary main jet remained as specified. The movement of the needle was carried out by a RS type 318-711 stepping linear actuator with corresponding control driver. A lead-tolerant Lambda sensor LSM11 was used to detect real-time operating air/fuel equivalence ratio. The air/fuel equivalence ratio was displayed on a BOSCH Lambda indicator LA2. With the above set-up, the operating air/fuel equivalence ratio of the engine can be adjusted to the nearest 0.01.

3.2.3 Measurement of Knock Response of Engine

The knock response of the engine was measured in terms of the knock limited spark advance (KLSA). The KLSA is defined as the degree of spark advance that the fuel will tolerate before the onset of trace knock. It is widely accepted that human ear is the most sensitive device to pick up the occurrence of engine knock. However, this audible knock detection method has several disadvantages. A well trained operator is required to carry out the determination, and because of this, the result would be subjective to the feeling of the operator whether knock is present or not. Moreover, it is difficult to identify the onset of trace knock. This is particularly a problem at high engine speed where other engine generated mechanical noise becomes dominant. It was found that a trained technician defined the borderline knock to be the spark timing at which 80% of the cycles were knocking. Beside the subjective problem, there is a hazard of having a person inside the altitude test cell when it is under depression.

To compare the anti-knock quality of the two fuels, KLSA is quantified as the spark timing at which the occurrence of knock phenomenon exceeds a certain percentage of the engine cycles.

A modified method of that proposed by Westerholm^[35] was adopted in this investigation as described below.

The engine was firstly stabilized at the specified test conditions with a knock-free spark timing. The spark timing was, then, advanced gradually until knock pressure traces started to appear on the oscilloscope screen. After running for 30 seconds, the acquisition system was triggered to record cylinder pressure and spark timing for a number of engine cycles. Due to the fluctuation of the distributor position, the actual spark timing covered approximately two degrees. Subsequently, for every two degrees of spark advance, a number of engine cycles were recorded. The procedure was repeated until the timing was 10 crank angle degrees advance from the starting point. Thus, both normal and knocking engine cycles were recorded for later analysis.

Owing to the limit in the scope segment buffer size of the computerscope, with 0.2 °CA measuring resolution, only nine consecutive engine cycles could be recorded. It was found that this gave a poor repeatable KLSA results (about 5 degrees' variation). Due to the random nature of engine knock, a larger number of engine cycles must be analysed to provide a statistically significant results. In order to increase the numbers of engine cycles for each spark-advance point, the data acquisition was carried out under the "triggered mode". In the "triggered mode", the measuring range can be varied instead of having a continuous sample over the whole 720 °CA engine cycle. The measuring range was set from -40 °CA to +164.8 °CA, which is the minimum scope segment (1 byte) allowable in the "triggered mode". Consequently, a maximum number of 32 engine cycles could be recorded. However, due to the data transfer time (from scope segment buffer to the RAM buffer) at the end of each triggered sampling, engine cycles could not be acquired consecutively. Depending on engine speed, pressure traces were acquired for each two to three cycles. Despite the non-consecutive data acquisition, the KLSA results were found to be repeatable within ± 1 °CA.

A program was written to separate the recorded scope binary data files into individual cycles and converted them into ASCII data file, which could be imported to a Quattro Pro spreadsheet. With the aid of spreadsheet graph plotting, cycles with knocking combustion were isolated from the normal ones by visual inspection of the recorded pressure traces. A typical pressure trace of knock cycle is illustrated in Figure 3.2.

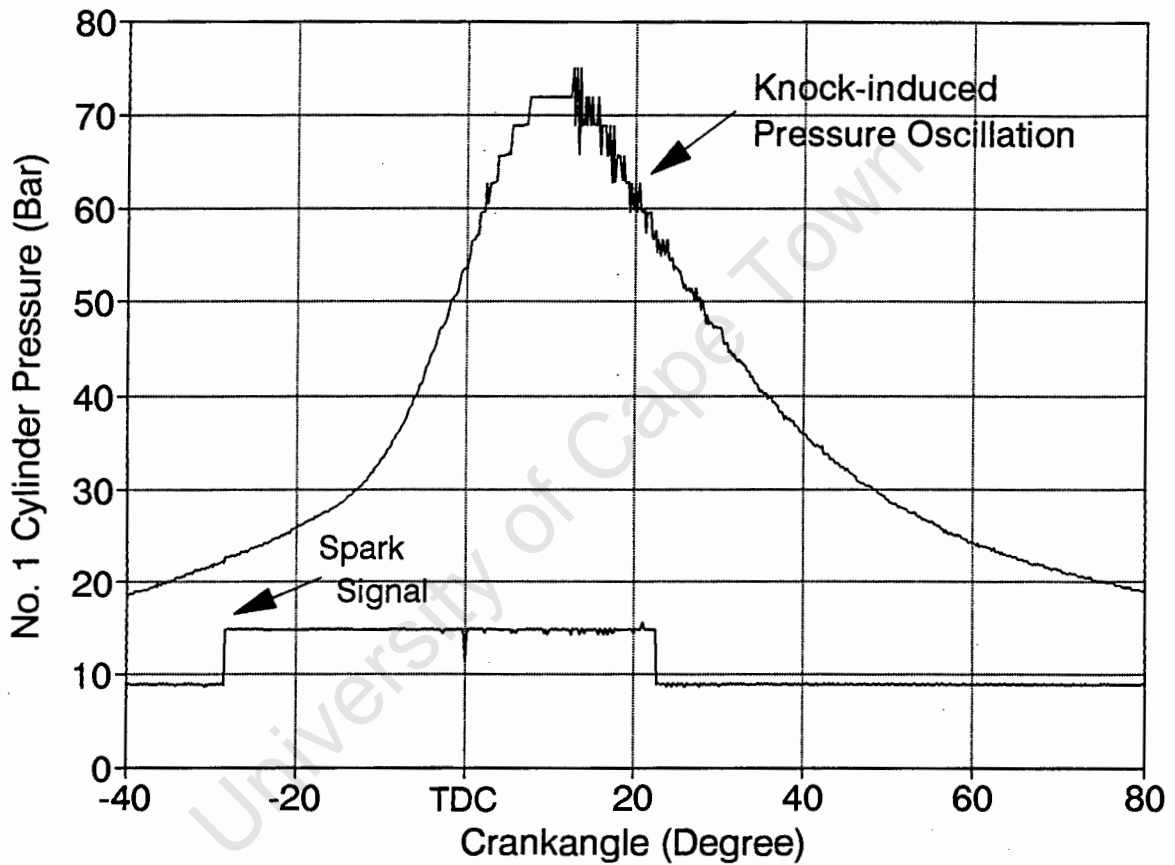


Figure 3.2 Pressure trace of knock cycle at 3500 rpm

Engine cycles were categorized by integral spark timing. For instance, cycles with spark timing between 26.5 and 27.4 °CA were grouped as "27 °CA". For each group, the percentage of knocking cycle was calculated. A typical results of this analysis is shown in Figure 3.3. It can be seen that knock cycles occur more frequently with increase in spark advance. Moreover, the increase in altitude increased the spark advance at which the

engine started to knock. The higher the altitude, the greater the spark advance at which knock cycles occurred at a certain frequency. The KLSA in this study was defined as the group in which engine knock occurs for more than 40% of the time.

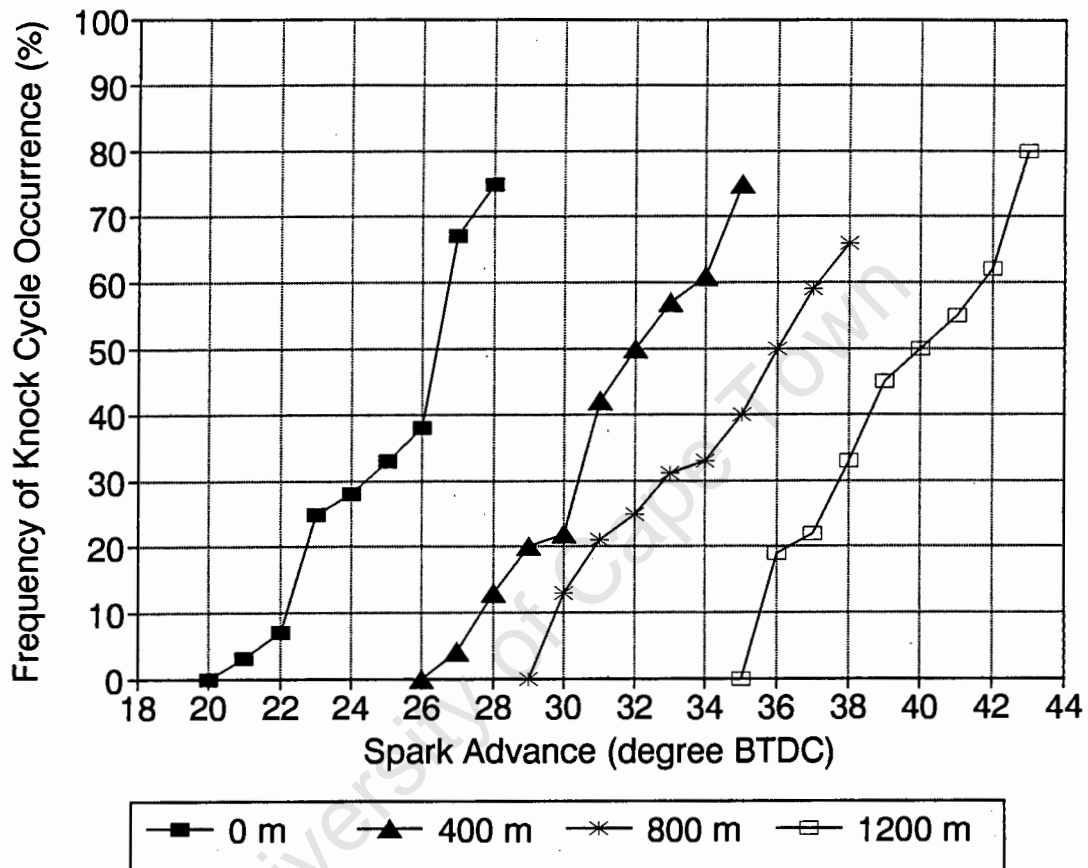


Figure 3.3 Graph shows the increase in knock occurrence frequency with spark timing

3.3 Experimental Procedure

Prior to the tests, preliminary tests were carried out with 97 pump fuel at wide-open throttle. The use of 97 pump fuel allowed the engine to run knock-free at standard timing at sea-level conditions. During the preliminary tests, inconsistent torque output was recorded at 2500 rpm. This was attributed to the erratic change in inlet manifold vacuum and operating air/fuel ratio. Examination of the carburettor showed that the secondary

throttle valve, which is actuated by a vacuum unit, opened to inconsistent positions at speeds ranging from 2200 rpm to 3000 rpm, depending on altitude. It was believed that the vacuum unit was faulty. To overcome the problem, the secondary throttle valve was mechanically linked to the primary one, such that at WOT both throttles were fully open. Thus all engine tests were carried out under this "WOTs" condition.

For each test fuel, engine tests were carried under a range of carburation settings, engine speeds and altitudes in a systematic test sequence, as listed in Appendix C. The sequence is designed to minimize the number of parameters (altitude, engine speed and needle position) adjusted between test points. At the sea-level carburation test points, the needle was away from the primary jet. At the Highveld carburation test points, for each test speed, adjustment was made to lean out the air/fuel ratio at 1200 m back to the sea level setting. Once the carburation was altitude compensated at 1200 m, the needle position was fixed and tests were performed at different altitudes. At the altitude-compensation test points, air/fuel ratios were adjusted at the test altitude to the corresponding sea level settings at each test speed.

At each test point, once the test point conditions were established, the engine was allowed to stabilize at a knock-free spark timing for at least one minute. All parameters were recorded and the computer was started to measure the fuel flow rate. The measurement procedure for KLSA determination were carried out as described in section 3.2.3. At each spark advance setting, the engine torque was recorded to allow for later determination of the KLSA torque. At the end of the KLSA procedure, which took approximately 6 minutes, the spark timing was set to the standard value to record the standard timing torque. Then, the spark advance was retarded to the initial "stabilization" timing. All parameters were again recorded and checked with the initial values. This was done to bring the engine to knock-free conditions after the operation under knocking conditions. The "initial" and "final" measurements were found to agree to within one percent.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of Altitude on Engine Performance

4.1.1 Carburation

The sea-level operating points of the original (sea-level) carburettor, with both test fuels, are summarized in *Table 4.1*.

Table 4.1 Sea-level operating points of the original carburettor

Speed (rpm)	Air/fuel Equivalence Ratio	
	Coastal 93	Ethanol Blend
1500	0.90	0.97
2500	0.79	0.86
3500	0.84	0.93
4500	0.83	0.87

It is worth mentioning that the mixture leaning effect of the ethanol blend observed in the experiments was a consequence of change in the stoichiometric air/fuel ratio coupled to an *actual reduction* in fuel flow into the engine. The anomaly of the drop in fuel flow with the ethanol blend could be attributed to a drop in fuel density as a result of temperature rise of some 15% in the float chamber during the tests. However, the cause of the temperature rise is uncertain.

As one would expect, the air mass flow into the engine decreased with altitude as the result of reduction in air density. This is shown in *Figure 4.1*.

The response of the carburettor to altitude change, as the result of the decrease in air mass flow, under different carburation settings, is illustrated in *Figure 4.2*. Similar 'Z' trends were obtained for both test fuels, regardless of engine speeds. The

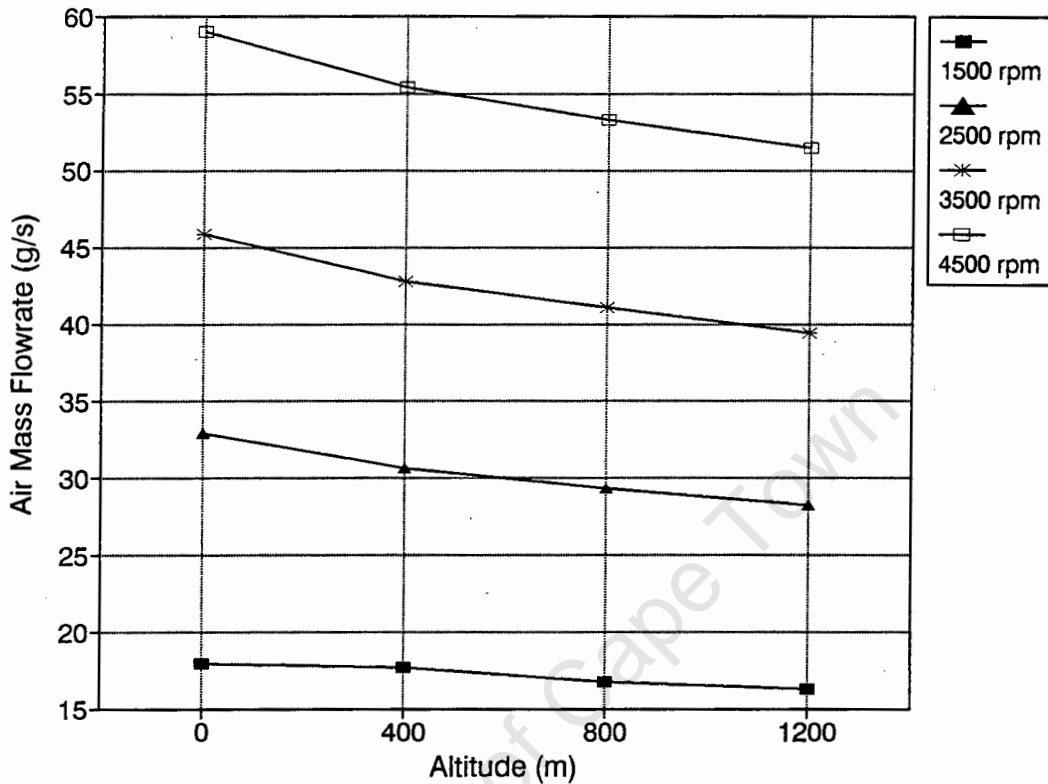


Figure 4.1 Air mass flow rate vs altitude

top and bottom lines show the change in air/fuel equivalence ratio for the Highveld and sea-level carburation setting respectively. The horizontal line was achieved by manual control of the carburation. Thus, each line represents the effect of altitude on carburation under different practical driving situations. The obvious result from Figure 4.2 is that a vehicle equipped with a sea-level carburettor would experience enrichment in air/fuel mixture upon driving from sea level to higher altitudes. On the other hand, if a Highveld carburettor (one adjusted to meter air/fuel mixture in the same ratio at 1200 m as at sea level) is installed in a vehicle, the air/fuel mixture would be leaned out upon driving from Highveld to lower altitudes. The horizontal line in Figure 4.2 represents a vehicle with closed-loop fuel management system, where altitude has no effect on carburation.

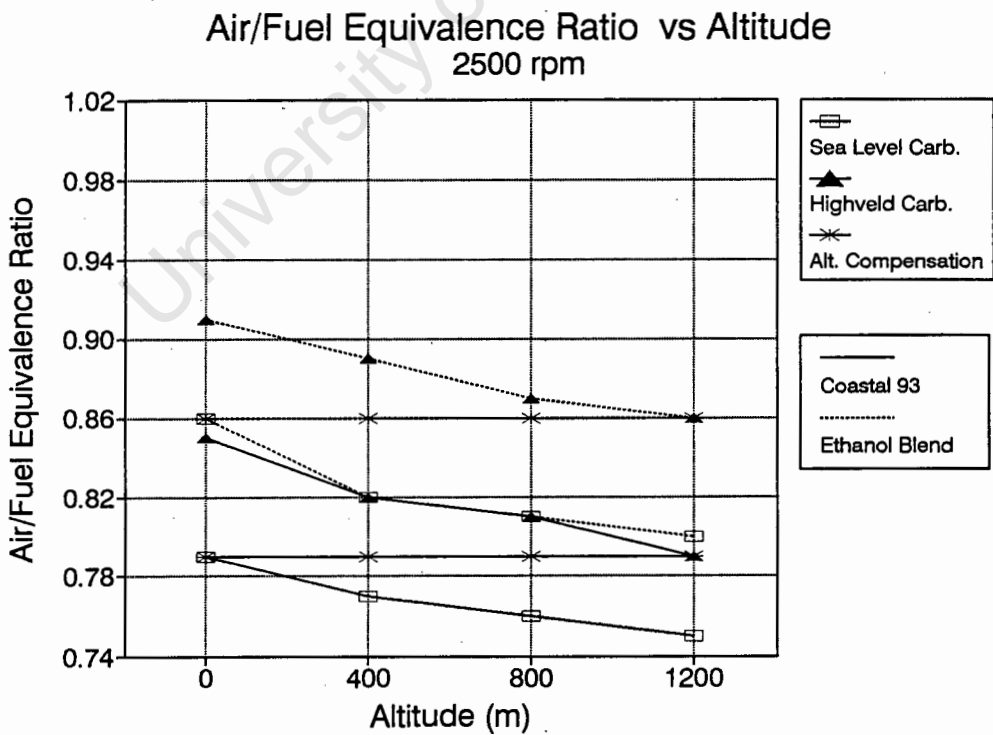
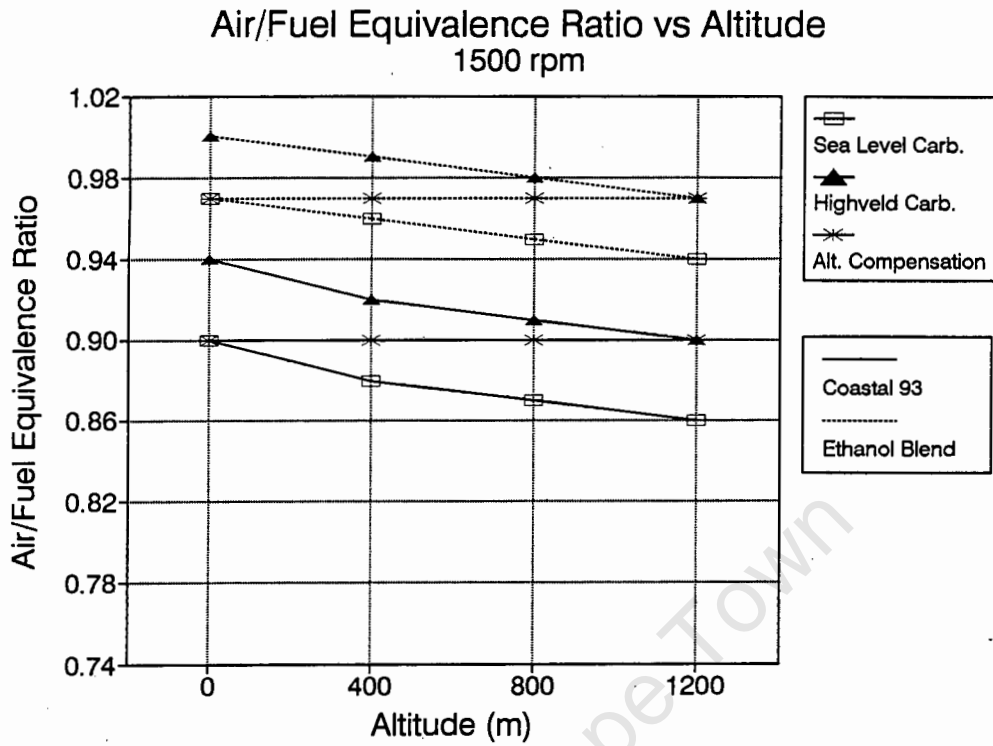


Figure 4.2a Graphs showing the effect of altitude on air/fuel equivalence ratio under various carburation settings

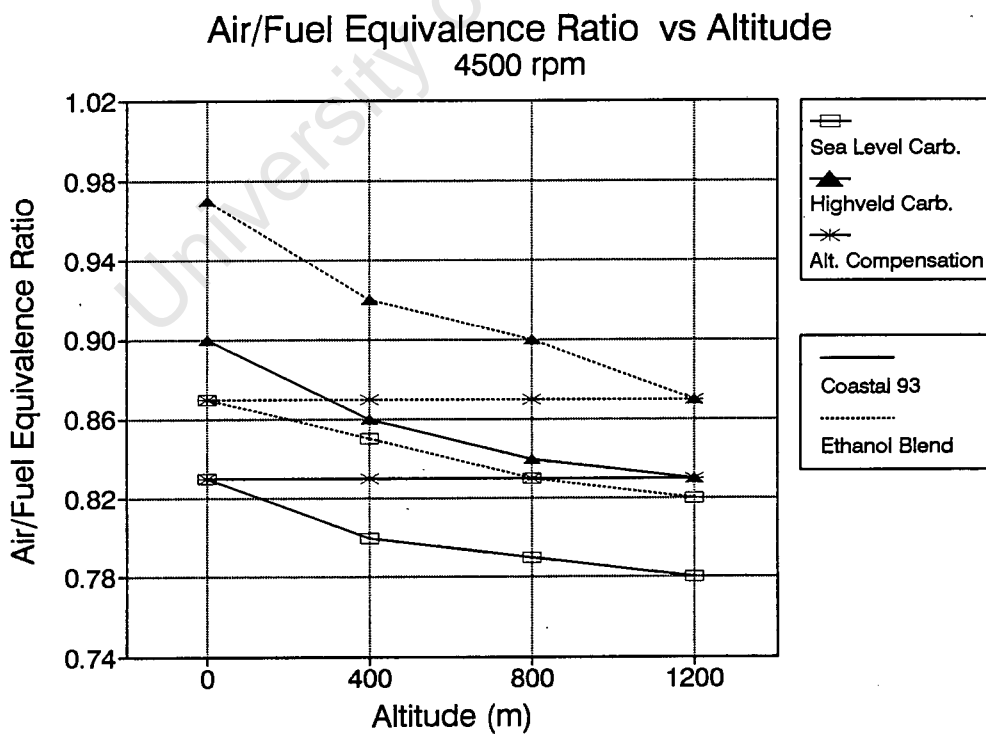
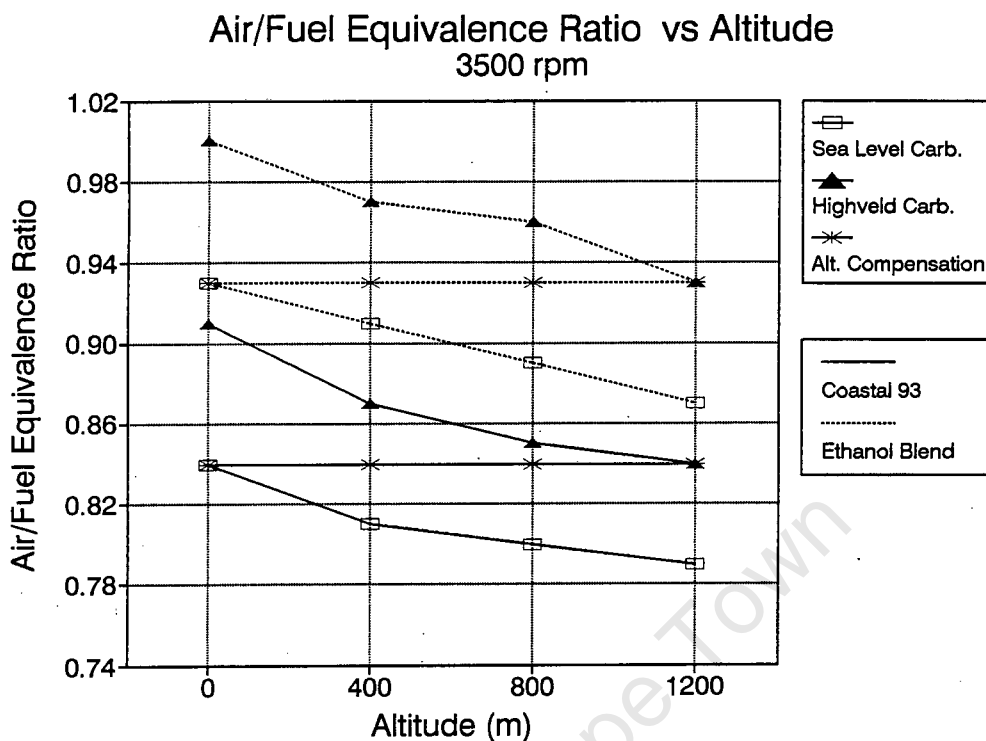


Figure 4.2b Graphs showing the effect of altitude on air/fuel equivalence ratio under various carburation settings

Table 4.2 summarizes the mixture enrichment at 1200 m with the sea-level carburation setting. The mixture enrichment is defined as the percentage change in air/fuel equivalence ratio to the original operating point. Similarly, the mixture leaning at sea level with the Highveld carburation setting is illustrated in Table 4.3.

Table 4.2 Mixture enrichment at 1200 m with the sea-level carburation setting

Speed (rpm)	Mixture Enrichment (%)	
	Coastal 93	Ethanol Blend
1500	4.4	3.1
2500	5.1	7.0
3500	6.0	6.6
4500	6.0	5.7

Table 4.3 Mixture leaning at sea level with the Highveld carburation setting

Speed (rpm)	Mixture Leaning (%)	
	Coastal 93	Ethanol Blend
1500	4.4	3.1
2500	7.6	5.8
3500	8.3	7.5
4500	8.4	11.5

Based on the test results, it can be concluded that the use of 10% ethanol blend leans out the absolute air/fuel mixture but does not change the extent of the altitude effect on carburation. In the other words, the amount of mixture leaning by the ethanol blend appeared to be independent of altitude.

4.1.2 Power Output and Fuel Economy

The reduction in engine torque and thus power at WOT with altitude are illustrated in *Figure E.1 to E.6* under various carburation settings, for both test fuels. Since the inlet air temperature was maintained at 50 °C throughout the tests, the reduction in engine torque output was purely the result of pressure reduction. As expected, upon operating the engine from sea level to an altitude of 1200 m, with a pressure reduction of 13.8 kPa, reductions of 16 to 20 percent in engine power (at standard timing) were recorded. However, abrupt drops in engine torque at certain test points, when operated at 1500 rpm, were observed. This could be attributed to the severe knocking conditions at those test points. Comparing the results from various carburation settings, the effect of altitude on carburation appeared to have no significant effect on engine power output. With the use of the ethanol blend, drops of 1 to 3 percent in engine power were observed. This is expected as the result of lower heating value of the ethanol blend.

Owing to the power drop and mixture enrichment with altitude, a substantial reduction in fuel economy was recorded. The effect of altitude on the brake specific fuel consumption (bsfc) are shown in *Figure E.7 and E.9*, for various carburation settings.

In an attempt to evaluate the effect of altitude on bsfc under various carburation settings, graphs of bsfc as a function of air/fuel equivalence ratio are plotted in *Figure 4.3*. It can be seen that bsfc increases with altitude as the air/fuel mixture becomes richer. Similar trends exist between the sea-level carburation and Highveld carburation settings for both test fuels. The increase in bsfc as a result of power reduction with altitude was shown by the altitude compensation test (vertical lines in the graphs), in which the effect of altitude enrichment on bsfc is isolated. The effect of air/fuel equivalence ratio on fuel economy can readily be seen by looking at the bsfc values at the same altitude with the three different carburation settings. It will be observed that there is a definite decrease in bsfc as the air/fuel mixture becomes leaner.

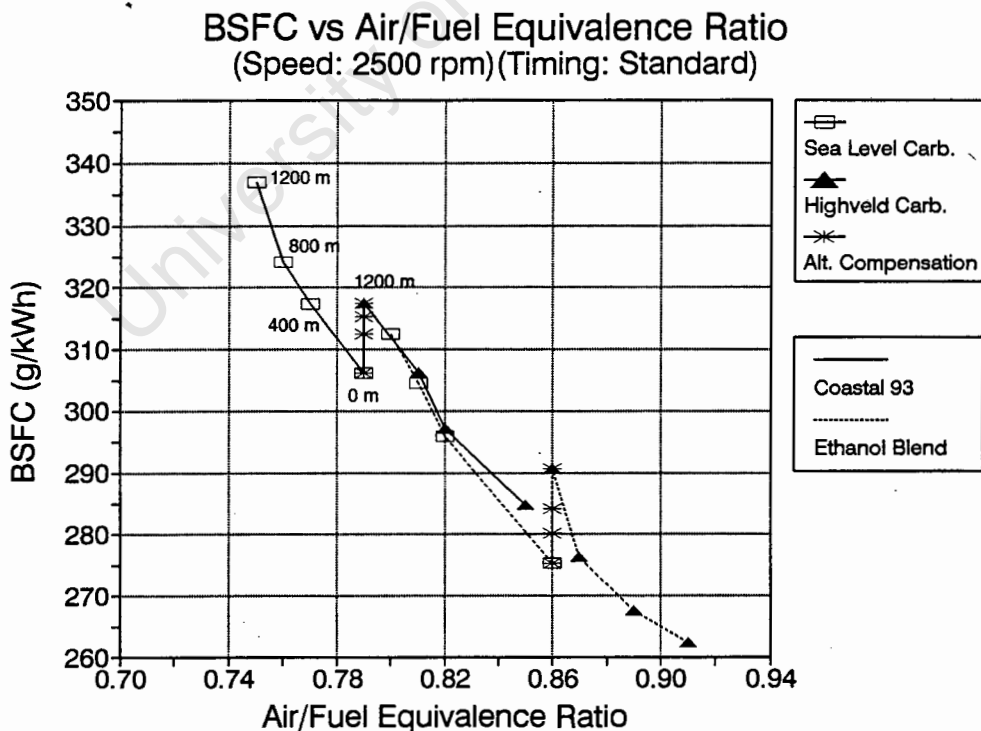
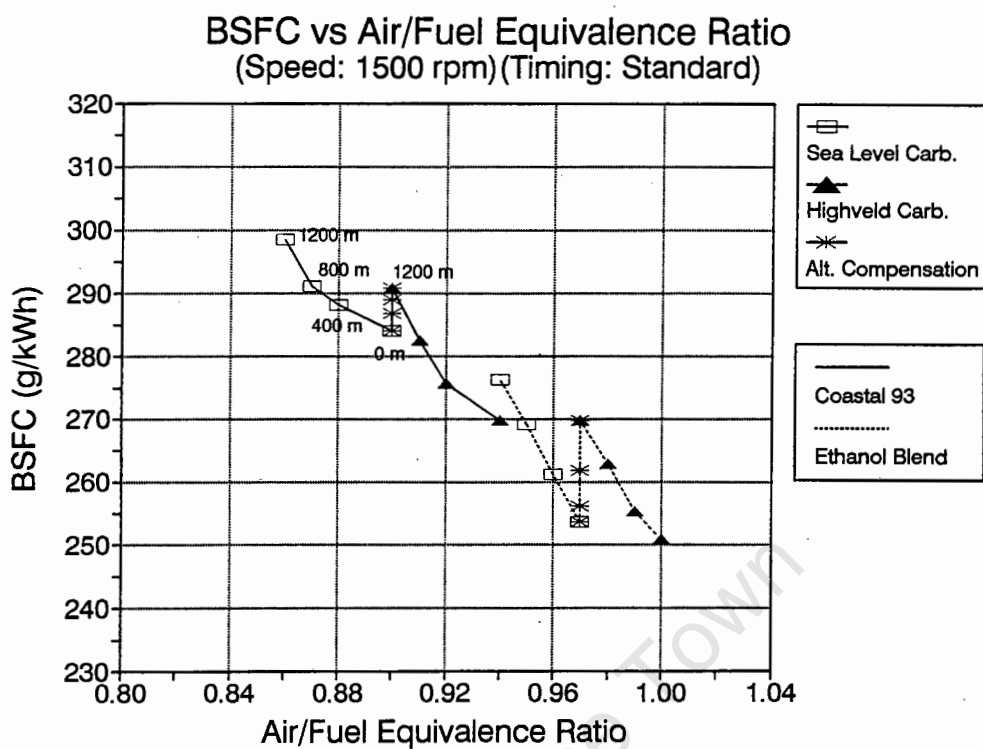


Figure 4.3a Graphs showing the variation in bsfc with altitude as a function of air/fuel equivalence ratio

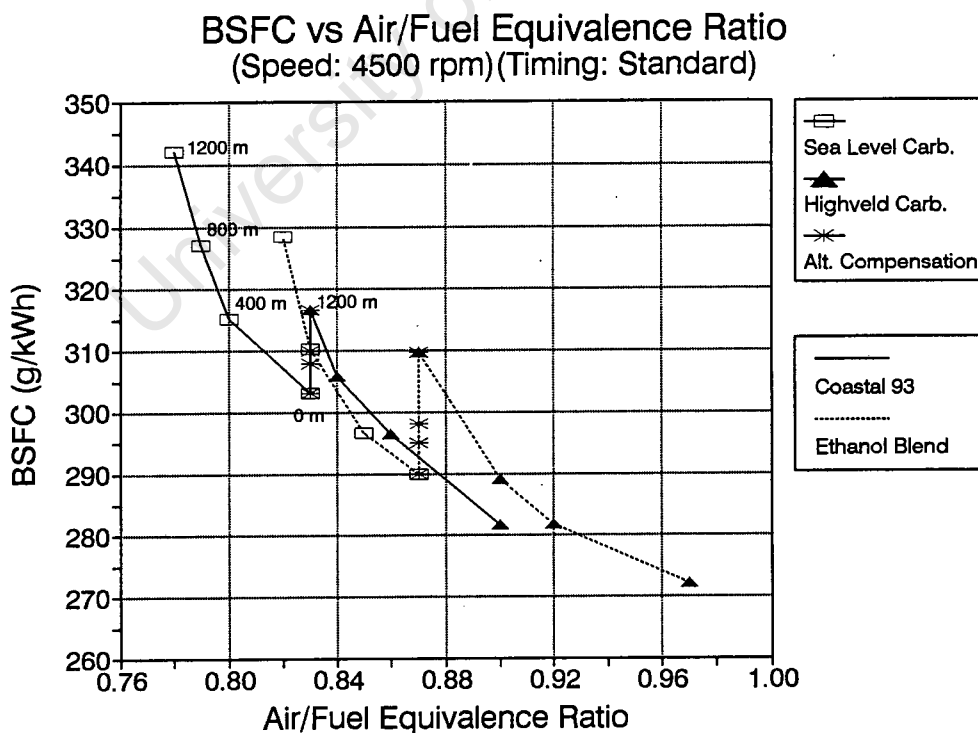
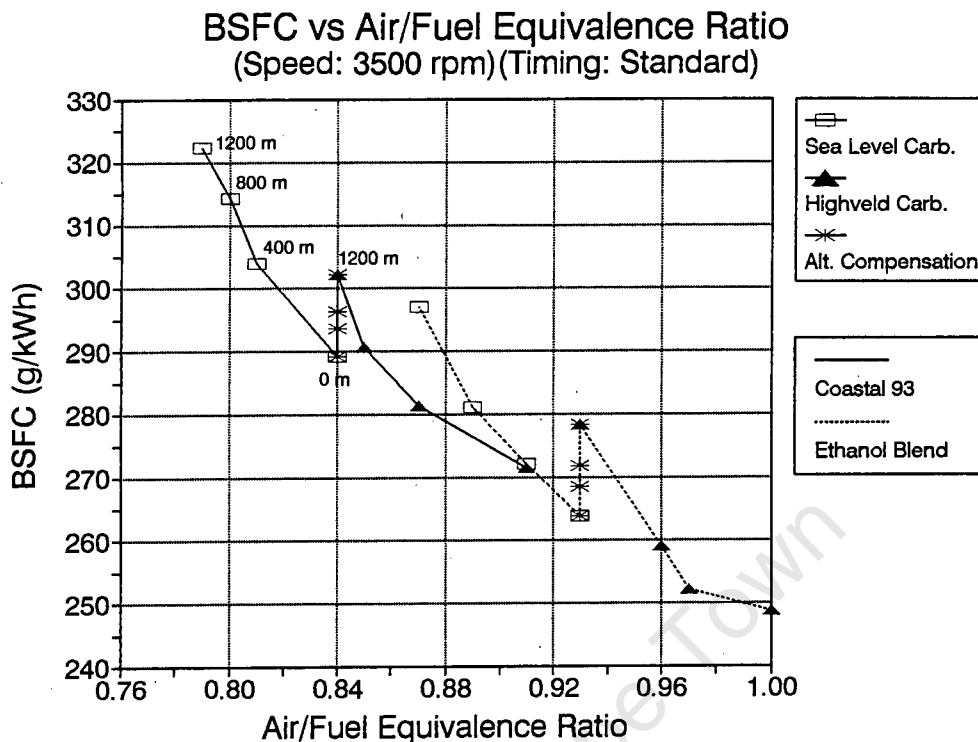


Figure 4.3b Graphs showing the variation in bsfc with altitude as a function of air/fuel equivalence ratio

As indicated by the result of the altitude-compensation test, the impact of altitude on fuel economy could be significantly alleviated. Results from the Highveld carburation test suggested that bsfc can be reduced by the use of a leaner air/fuel mixture. The improvement in fuel economy can be explained by the increase in fuel conversion efficiency with leaner mixtures.

Comparison of the impacts of altitude on fuel economy without and with altitude compensation for both test fuels are shown in Table 4.4, as a percentage increase in bsfc upon driving from sea-level to 1200 m.

Table 4.4 Percentage increase in bsfc at 1200 m without and with altitude compensation

Speed (rpm)	Sea-level Carburation		Altitude Compensation	
	Coastal 93	Ethanol Blend	Coastal 93	Ethanol Blend
1500	4.9	8.7	2.5	6.3
2500	10.1	13.5	3.6	5.8
3500	11.4	12.5	4.5	5.3
4500	12.9	13.1	4.6	6.9

Although there appears to be a greater percentage increase in bsfc at high altitude, particularly at low engine speeds, with the ethanol blend, the fuel economy is significantly improved by the ethanol blend. The improvement in fuel economy of the ethanol blend compared to the straight gasoline is shown in Figure 4.4. The finding is, however, contrary to the expectation of a similar or a slight reduction in fuel economy with the use of ethanol blend. This could be attributed to the further mixture leaning as the result of the unexpected drop in fuel flow into the engine during tests with the ethanol blend, as mentioned in the previous section.

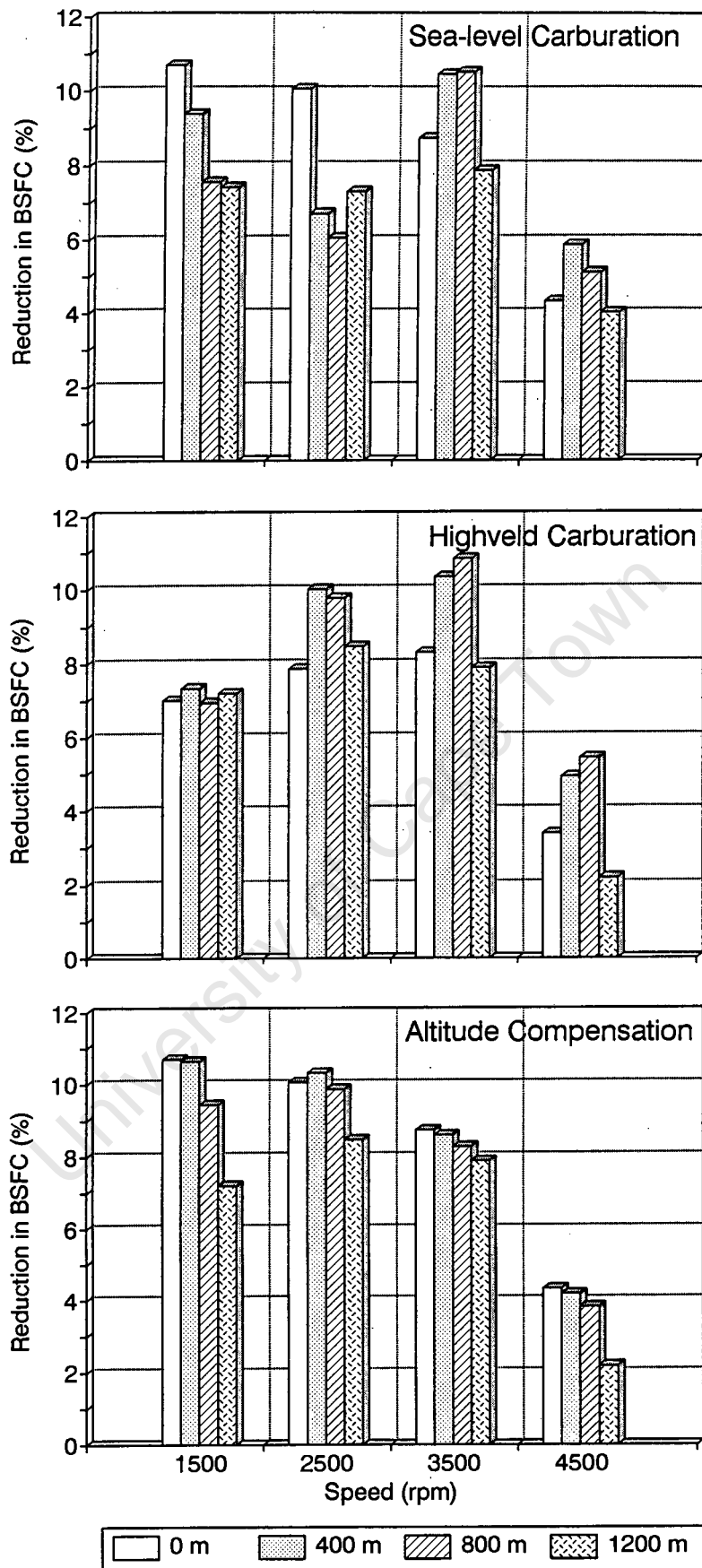


Figure 4.4 Reduction in bsfc by the ethanol blend with various carburation settings

4.1.3 Exhaust CO Emission

The influence of altitude on exhaust CO emission is illustrated in *Figure E.10 to E.12* under various carburation settings, for both test fuels. It can be seen that higher CO emissions are expected at high altitudes except when the engine is equipped with an altitude compensation carburation system. However, the rate of increase is somehow different between the coastal 93 fuel and the ethanol blend.

To evaluate the effect of altitude on CO emission, graphs of exhaust CO emission as a function of air/fuel equivalence ratio were plotted in *Figure 4.5*. The graphs show that the CO concentration in the exhaust gas increase linearly with decreasing air/fuel equivalence ratio, as the amount of excess fuel increases. A similar linear relationship is observed independent of engine speeds and the test fuels, except when operating close to stoichiometric conditions. Thus, it is obvious that the exhaust CO emission depends exclusively on mixture stoichiometry. Consequently, the increase in exhaust CO emission with altitude follows the altitude enrichment effect.

As indicated by the Highveld carburation test results, adjustment of carburation set points at high altitudes would be a fundamental means of reducing the impact of altitude on exhaust CO emission. Results from the altitude compensation test indicate that the reduction in barometric pressure with altitude does not have a perceptible effect on exhaust CO emission. The marginal differences in the measured CO emission are considered as due to experimental variation. Thus, it can be deduced that an engine with closed-loop fuel management system would not experience any increase in CO emission when operating at high altitude.

Operating the engine with the ethanol blend has a significant benefit in reducing the absolute CO emission through the mixture leaning effect. The reduction in CO emissions with the use of ethanol blend under various carburation settings are shown in *Figure 4.6*. Reductions in CO emission from 20% to 70% were observed. It is obvious that the amount of CO reduction by the ethanol blend essentially depend on the operating carburation set points.

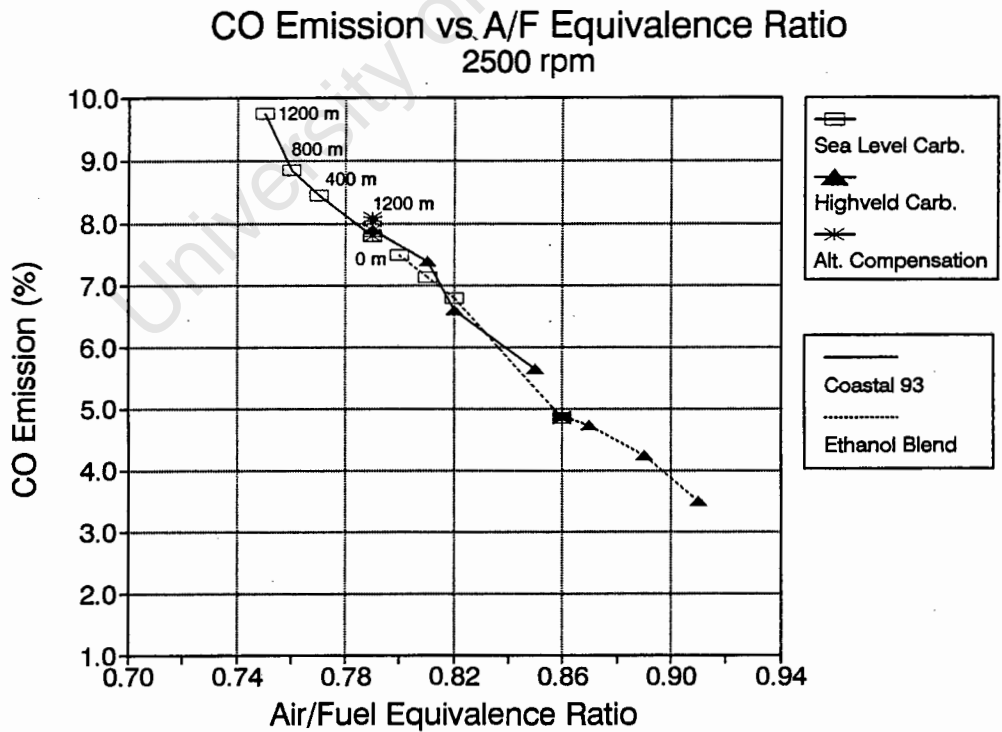
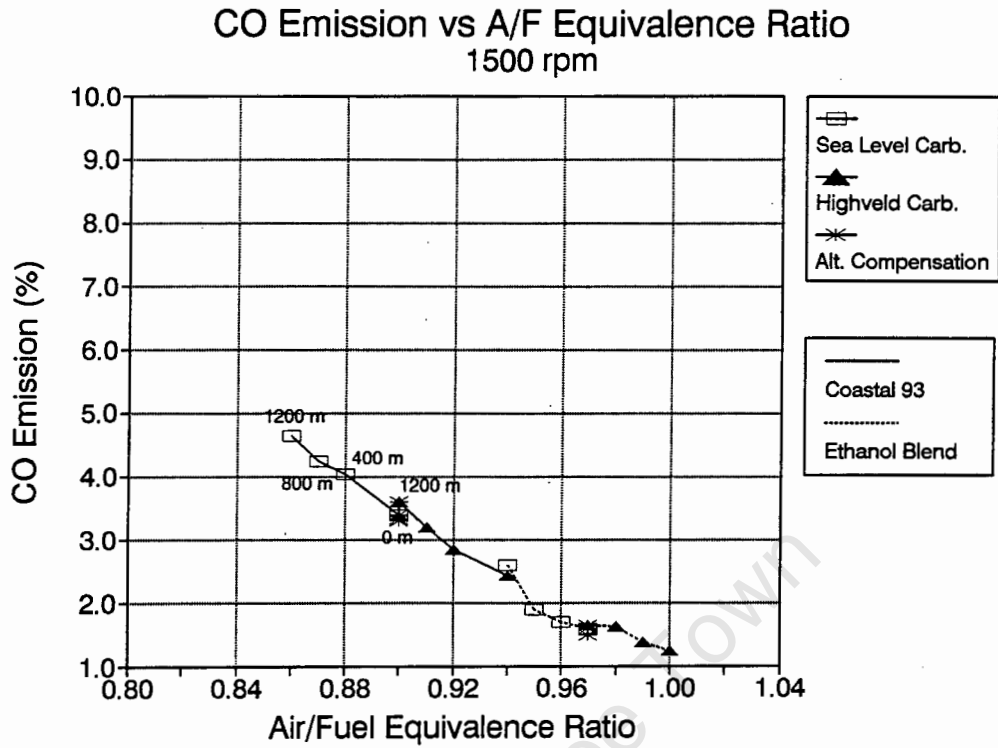


Figure 4.5a Graphs showing the influence of altitude on exhaust CO emission as a function of air/fuel equivalence ratio

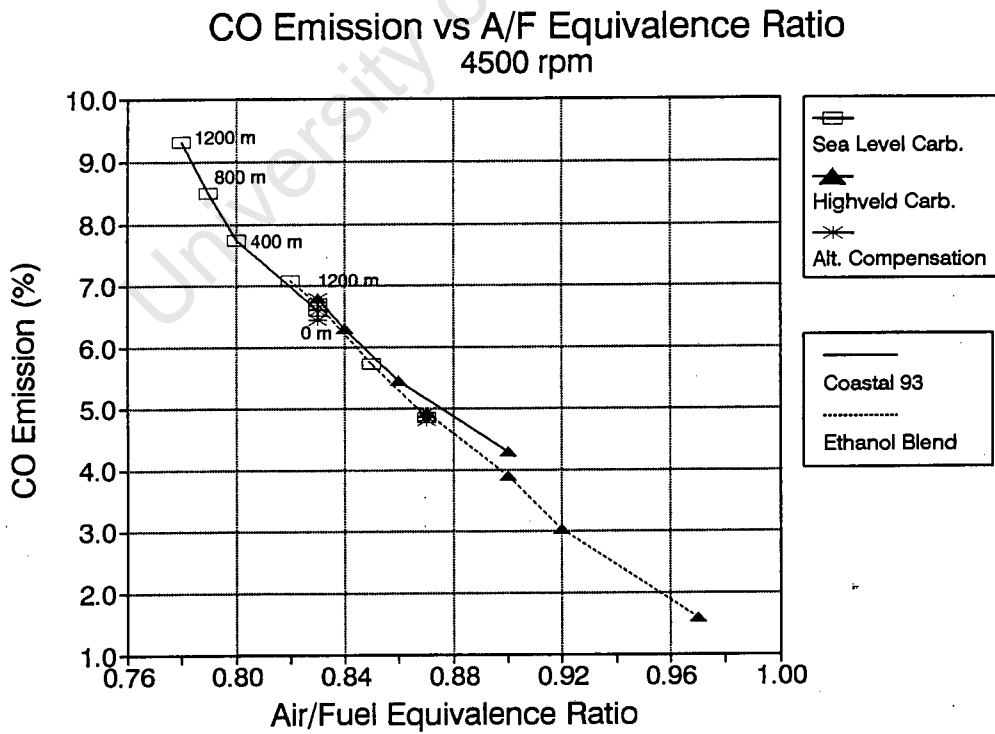
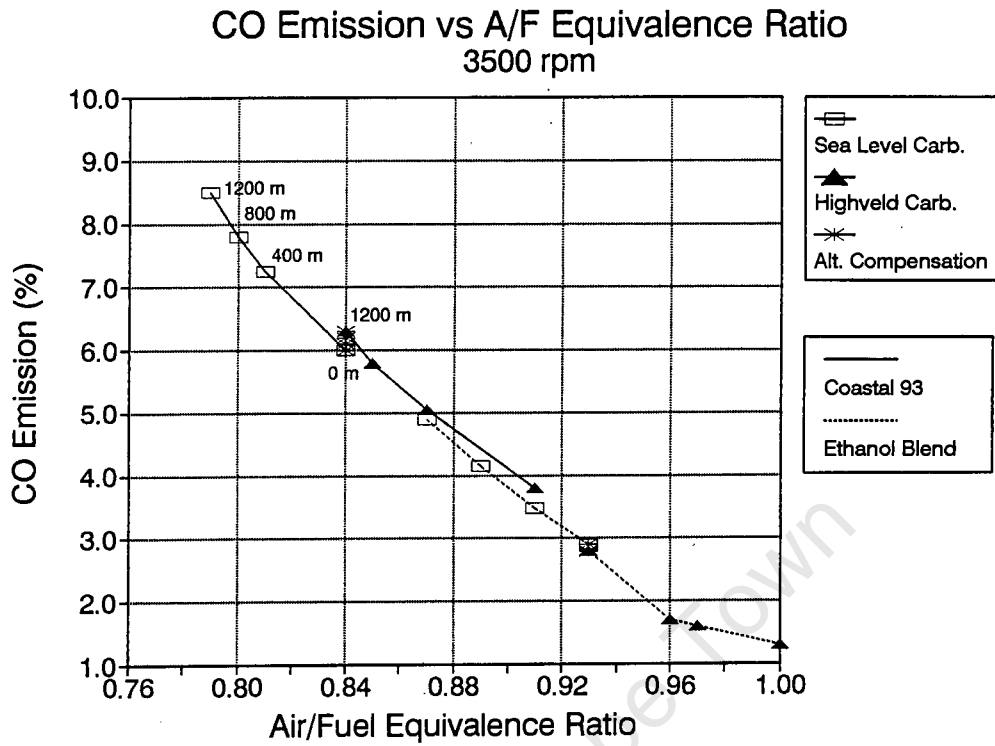


Figure 4.5b Graphs showing the influence of altitude on exhaust CO emission as a function of air/fuel equivalence ratio

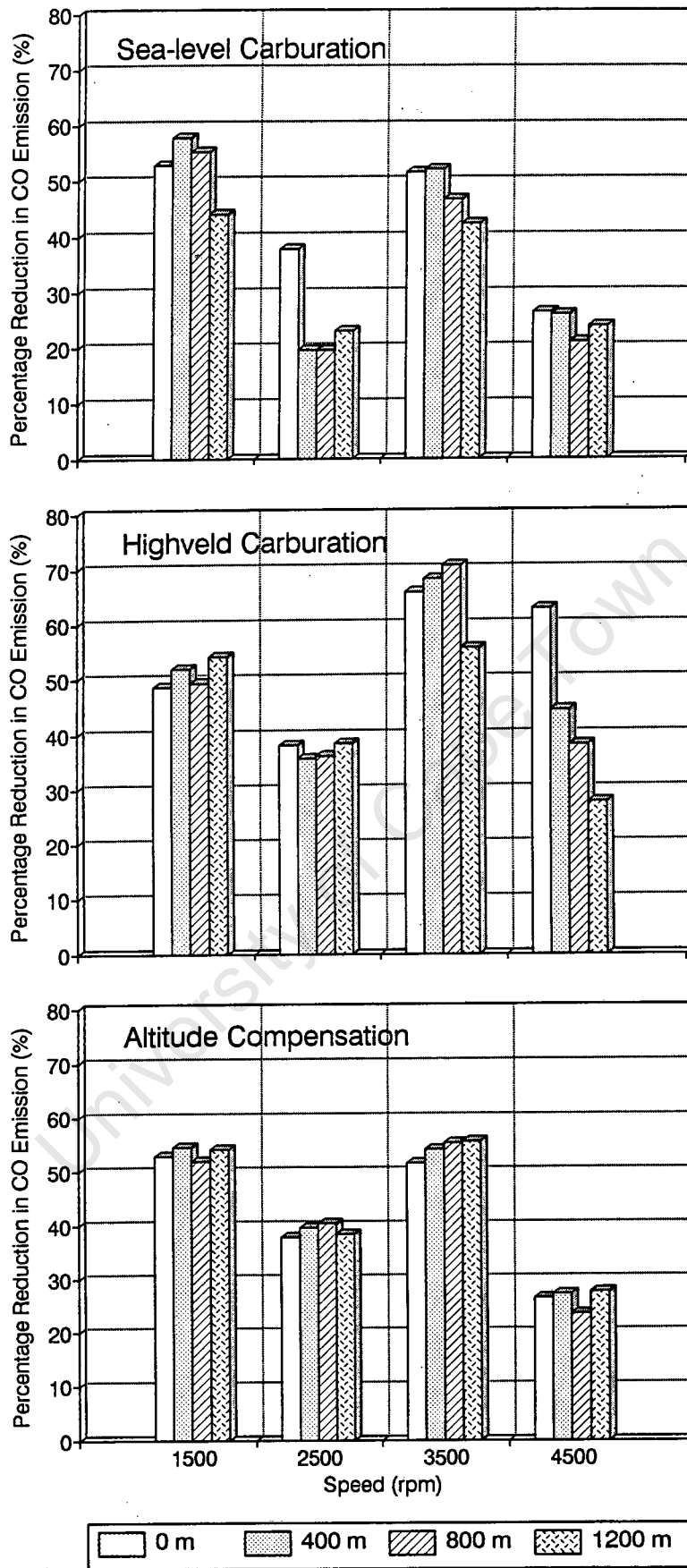


Figure 4.6

Reduction in exhaust CO emission by the ethanol blend with various carburation settings

4.2 Effect of Altitude on Engine Knock Response

4.2.1 Knock Limited Spark Advance

The knock response of an engine is quantified in terms of KLSA in order to compare the influence of altitude on engine knock, under different operating conditions and with different fuels. The KLSA is defined as the spark timing at which engine knock occurs for more than 40% of the time, by the method described in Section 3.2.3. The repeatability of the measurement technique of KLSA was found to be within ± 1 °CA. Therefore, the response of the engine to knock between two test points can be considered as significantly different only if there is a difference in KLSA of two degrees or more.

As expected, resulting from the reduction in octane requirement of an engine with altitude, KLSA increases with a rise in altitude (*Figure E.13 to E.15*). However, the magnitude of the increase in KLSA between consecutive altitude increments were not necessarily the same. It appeared that the increase in KLSA was generally more significant in the first 400 m altitude rise from sea level, particularly with the ethanol blend. The increase in KLSA values at 1200 m compared to the sea-level values is summarized in *Table 4.5*.

Table 4.5 Increase in KLSA values at 1200 m, from the sea-level values

Speed (rpm)	Coastal 93			Ethanol Blend		
	Sea Level Carburation	Highveld Carburation	Altitude Compensation	Sea Level Carburation	Highveld Carburation	Altitude Compensation
1500	9	9	9	8	7	9
2500	13	13	11	12	8	8
3500	14	12	11	13	10	10
4500	13	11	10	12	9	9

The relationship between KLSA and engine speeds against the altitude change is outlined in *Figure E.16 to E.18*, with the manufacturer's spark advance curve and maximum brake torque (MBT)

spark timing curve, at WOT, superimposed. The MBT spark timings were determined with Avgas fuel (RON 103), to ensure knock-free condition, in a previous engine test.

The strong correlation between KLSA and engine speed is apparent from the figures. Moreover, it can be seen that the KLSA curves, for various carburation settings and for both test fuels, closely follow the trend of the manufacturer's spark advance curve, except in the low speed regime when operated on the coastal 93 fuel. In a "real-life" situation, whether an engine will knock under certain operating conditions depends on the manufacturer's spark advance calibration. It was found that the engine would not be able to run knock-free, with both test fuels, at WOT with the manufacturer's spark advance calibration under the sea-level conditions, with inlet air pressure and temperature of 101.3 kPa and 50 °C. In the other words, the anti-knock quality of both test fuels is not high enough to satisfy the octane requirement of the engine at sea-level. The reduction in octane requirement of the engine with altitude gives the engine increasing KLSA values. Consequently, at altitudes higher than 400 m the engine will operate knock-free (at WOT) with both test fuels, except with the coastal 93 fuel at 1500 rpm, which exhibits knock-free operation only at 1200 m altitude.

Comparing the manufacturer's spark advance curve with the MBT spark timing curve, it is clear that the spark advance calibration is retarded from the optimum values at MBT, as a means of avoiding engine knock when operated with normal commercial fuels. Thus, engine knock problems indirectly lead to lower power output and hence fuel economy of an engine. However, if the KLSA timing is higher than the MBT timing, engine knock should virtually impose no effect on engine power and fuel economy, since the engine can be operated at the optimum MBT timings without risk of engine knock. In this respect, the benefit of a rise in altitude with increasing KLSA values is obvious. At 1200 m, except with 1500 rpm, the engine showed higher KLSA values than the MBT timing, for various carburation settings and for both test fuels. Consequently the engine could be operated at optimum timing leading to optimum power output and fuel economy. At sea-level the engine has to be operated at a

retarded timing from the optimum in order to run below the knock-limit (knocking for 40% of the time). As a result, the engine suffers from the engine knock impact of power and fuel economy reduction. However, the exact degree of reduction cannot be evaluated in this study, since it was not possible to determine the MBT of the engine with both test fuels, owing to severe knock operation. The effect of altitude on KLSA torque of the engine operating with both fuels and using different carburation settings is illustrated in *Figure E.22 to E.24*.

4.2.2 Engine Knock Protection

As mentioned previously, whether an engine will knock under certain operating conditions depends on the manufacturer's spark advance calibration. The difference between the measured KLSA from the standard spark timing is used as a measure of the degree of knock protection to the engine. The increase in knock protection with altitude is shown in *Figure E.19 to E.21*. It can be seen that, with the exception of 1500 rpm, the engine exhibits similar knock protection at various engine speeds. However, the knock protection is different with the two test fuels. Because of the increase in KLSA with altitude, the engine experienced an increasing degree of knock protection at high altitudes.

In order to evaluate the effect of altitude on the degree of knock protection under various carburation settings, knock protection is plotted as a function of air/fuel equivalence ratio in *Figure 4.7*. The standard spark timing of the engine is indicated by the zero line on the graphs. A negative quantity means that spark timing needs to be retarded from standard timing in order for the engine to run under the knock limit.

Examination of the results from the three different carburation test indicate that the impact of altitude on engine knock is attributed to the change in barometric pressure and the resulting variation in air/fuel equivalence ratio. The improvement in knock protection as a result of pressure reduction with altitude is shown by the altitude compensation test (vertical lines in the graphs), in which the effect of altitude on carburation is

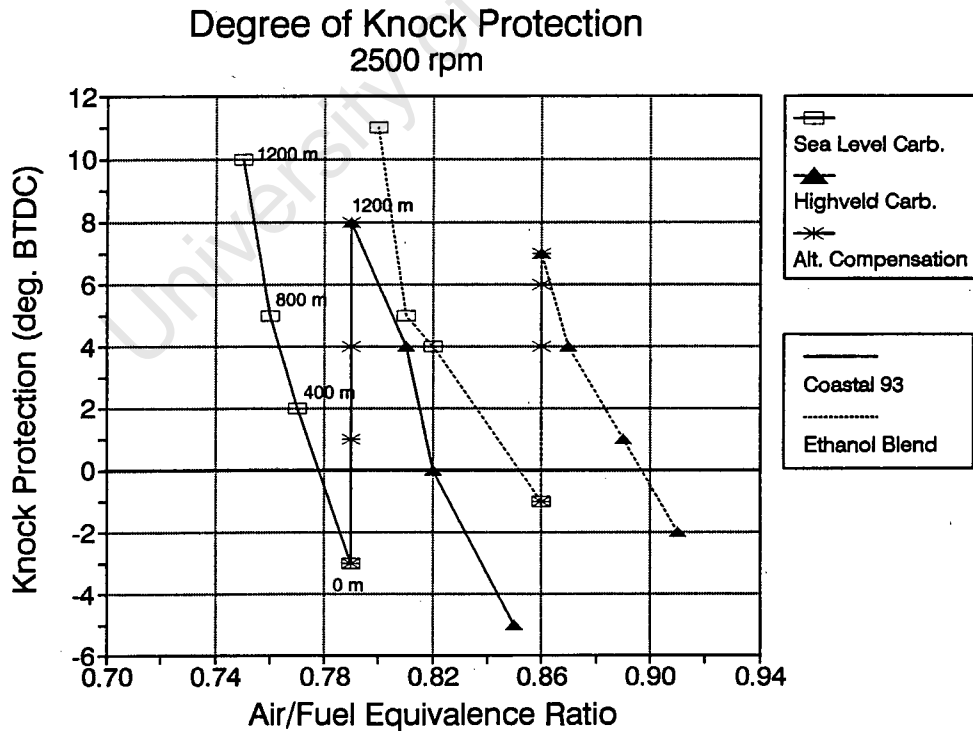
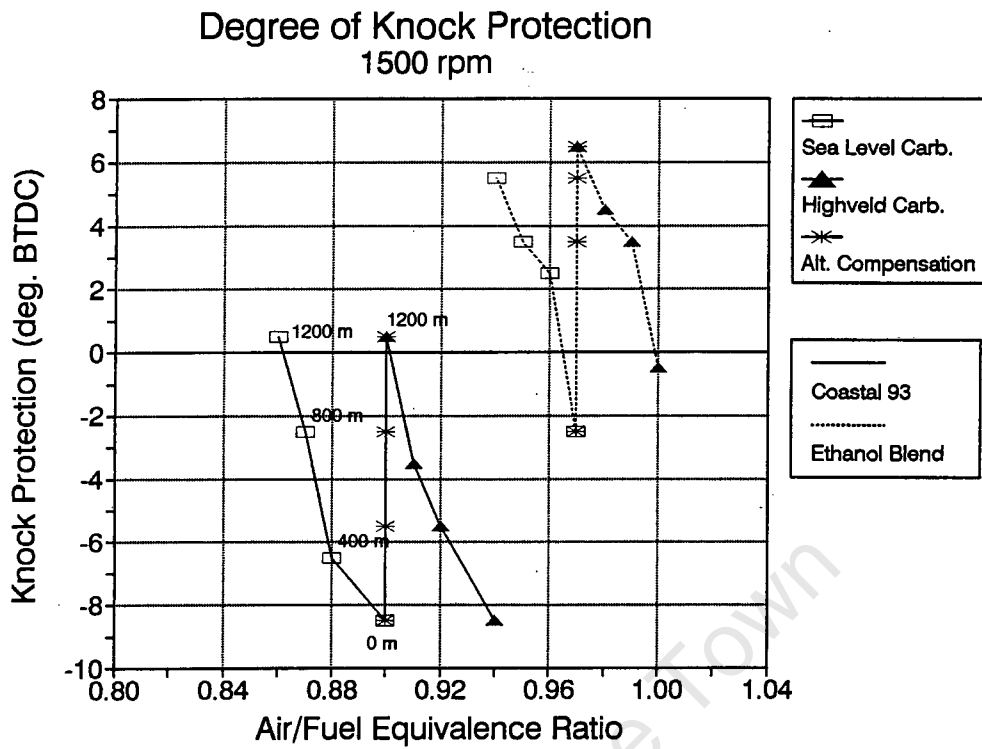


Figure 4.7a Graphs showing the effect of altitude on engine knock protection as a function of air/fuel equivalence ratio

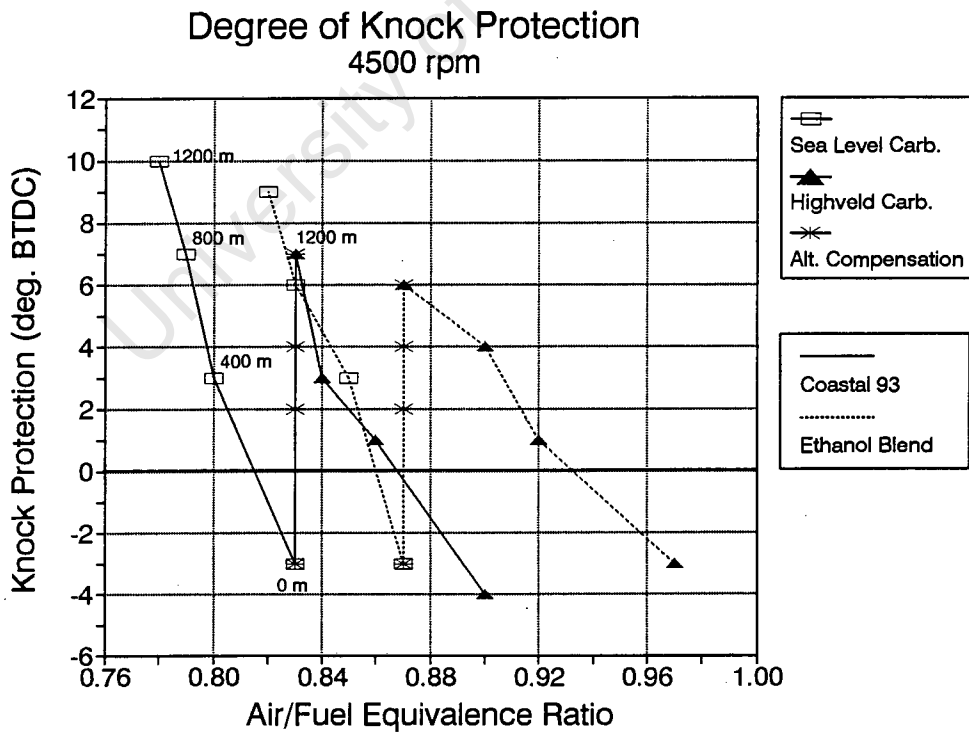
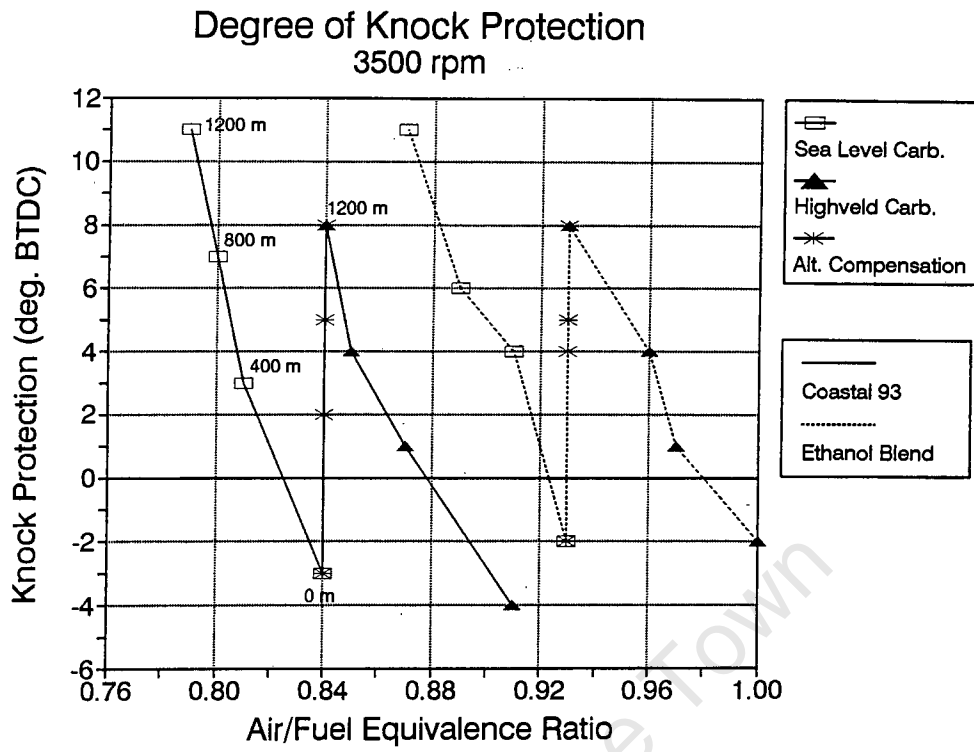


Figure 4.7b Graphs showing the effect of altitude on engine knock protection as a function of air/fuel equivalence ratio

isolated. The effect of air/fuel equivalence ratio on knock protection can readily be seen by looking at the degree of knock protection at the same altitude with the three different carburation settings. It will be observed that there is a definite increase in knock protection as mixture becomes richer, except at 1500 rpm with both test fuels, and at 2500 rpm with the ethanol blend.

Comparing the results from the sea-level carburation test with the altitude-compensation test, it is evident that, with both test fuels, the enrichment effect of altitude furnished the engine with some additional 1 to 3 °CA gain in knock protection. Compared to the sea-level carburation, with both test fuels, the use of Highveld carburation was found to have an adverse effect of diminishing the benefit of gain in knock protection with altitude. This can be explained by considering the basic engine carburation being on the rich side of that of maximum knock susceptible air/fuel ratio.

4.2.3 Comparison between the Test Fuels

Originally, it was desired to split-blend 10% ethanol to a blend stock so as to arrive at a similar RON/MON value to the coastal 93 fuel. However, the final ethanol blend turned out to have a higher RON/MON value (RON 95.3 and MON 85.4) than the coastal 93 fuel (RON 92.7 and MON 83.7). The anti-knock quality of the test fuels to satisfy the engine octane requirement at various altitudes is compared in term of the degree of knock protection to the engine.

Despite a higher RON/MON value of the ethanol blend, it did not improve the knock protection to the same extent for all the test speeds. At 1500 rpm the ethanol blend furnished the engine with a remarkable increase in knock protection. When running on the coastal 93 fuel, it was only at 1200 m (barometric pressure of 87.5 kPa) that the engine could marginally run at standard timing without exceeding the knock limit. However, with the ethanol blend, there was a 6 °CA knock protection under the same operating conditions. The improvement in knock protection with the use of the ethanol blend under different test conditions is summarized in *Figure 4.8*.

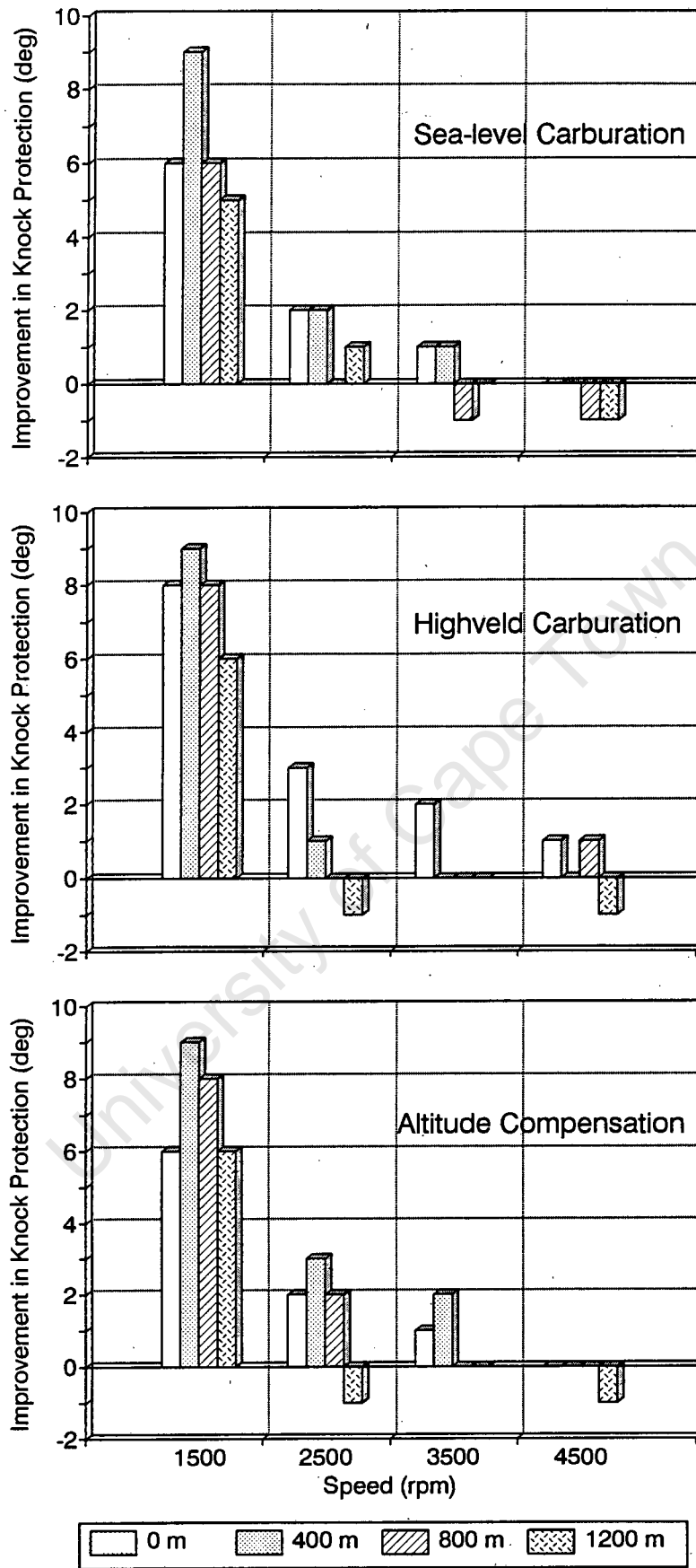


Figure 4.8 Improvement in knock protection with the ethanol blend

The test results indicate a sudden drop in knock protection with the ethanol blend as the engine speed was increased above 2500 rpm. At high engine speeds, the ethanol blend can only provide similar or slightly worse knock protection to the engine as that by the coastal 93 fuel. Based on the test results, the improvement in knock protection of the ethanol blend over the coastal 93 fuel was found to decrease significantly with an increase in engine speed and marginally with a rise in altitude. No differentiation could be observed for different carburation settings.

The benefit of blending 10% of ethanol to gasoline can be concluded as follows. Blending 10% ethanol to gasoline allows the use of a lower RON/MON blend stock, while the final blend could still have a similar anti-knock quality to some higher RON/MON base fuel used alone, at high engine speeds. In addition, a significant increase in knock protection will be expected in the low speed regime, where engine knock is more prone to occur with straight gasoline.

CHAPTER 5

CONCLUSIONS

The work described in this thesis has provided some insight into the effect of altitude on a locally mass-produced SI engine, under three different carburation settings. It has been shown that the influences of altitude on the engine is attributed to the reduction in barometric pressure and the resulting variation in air/fuel equivalence ratio. The benefits of using the 10% ethanol blend over the straight gasoline at altitudes are evident from the test results. The following conclusions can be drawn from this investigation.

5.1 Effect of Altitude on Engine Performance

5.1.1 Carburation

The enrichment effect of altitude on a conventional carburettor was confirmed. Based on the test results, a vehicle equipped with a sea-level carburettor would experience some 6 percent enrichment in air/fuel ratio upon driving from sea level to an altitude of 1200 m. It was found that the use of ethanol blend has only an effect of leaning out the absolute air/fuel mixture but does not change the extent of altitude effect on carburation.

5.1.2 Power Output and Fuel Economy

It has been shown that both engine power output and fuel economy decrease with an increase in altitude. The effect of altitude on carburation appeared to have no significant effect on power reduction at altitudes. Nevertheless, the enrichment in air/fuel mixture at altitudes substantially increased the bsfc of the engine. It was concluded that the impact of altitude on fuel economy could be minimized by using a close-loop fuel management system in the engine. Results from the Highveld carburation test suggested that further improvement in fuel economy is possible as the result of leaner air/fuel mixture. Contrary to the

expectation of a similar or a slight reduction in fuel economy with the use of ethanol blend, a significant improvement in the fuel economy was observed in the experiments. This anomaly was attributed to the further mixture leaning as the result of the unexpected drop in fuel flow into the engine during the tests with the ethanol blend.

5.1.3 Exhaust CO Emission

The theoretical linear relationship of exhaust CO emission with the air/fuel equivalence ratio was confirmed. It has been shown that the increase in CO emission with altitude resulted solely from the enrichment effect of altitude on carburation. Thus, it would appear that an engine with closed-loop fuel management system would not experience any increase in exhaust CO emissions when operating at high altitudes. The use of the ethanol blend has a significant benefit in reducing the absolute CO emission through the mixture leaning effect. It was concluded that the amount of CO reduction by the ethanol blend essentially depends on the operating carburation set points.

5.2 Effect of Altitude on Engine Knock Response

The effect of altitude on engine knock response has been evaluated in terms of KLSA, which was determined under the criterion of engine knocking for 40% of the time. It has been shown that the increasing KLSA values with altitude result in improvement in knock protection to the engine at altitudes. While the engine can be operated knock-free at altitudes higher than 400 m, the anti-knock quality of both test fuels is not high enough to satisfy the octane requirement of the engine under sea-level conditions. With the coastal 93 fuel, knock-free operation at low speed was found to be possible only at 1200 m altitude.

An examination of the test results from different carburation tests revealed that the enrichment effect of altitude furnished the engine with some additional 1 to 3 °CA gain in knock

protection. Installation of a Highveld carburettor to an engine would have an adverse effect of diminishing the benefit of gain in knock protection with altitude.

Compared to the straight gasoline, the ethanol blend has a higher anti-knock quality, in terms of degree of knock protection, at low engine speed. However, the gain in knock protection by the ethanol blend was found to decrease significantly with an increase in engine speed and marginally with a rise in altitude.

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APPENDICES

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APPENDIX A
ENGINE DETAILS

Engine: Toyota RS1600 (4A-F)

Configuration: In-line four cylinder

Capacity: 1587 cc

Bore: 81.0 mm

Stroke: 77.0 mm

Compression ratio: 9.5 : 1

Valve gear: Twin overhead camshafts
4 valves per cylinders

Fuel management: Downdraught twin barrel carburettor
main jets - primary: 1.04 mm
secondary: 1.59 mm

Standard spark timing: 10° BTDC @ 900 rpm

Spark plug: C7YC

Combustion chamber: Penthouse

Maximum power: 70 kW at 6000 rpm

Maximum torque: 135 Nm at 3600 rpm

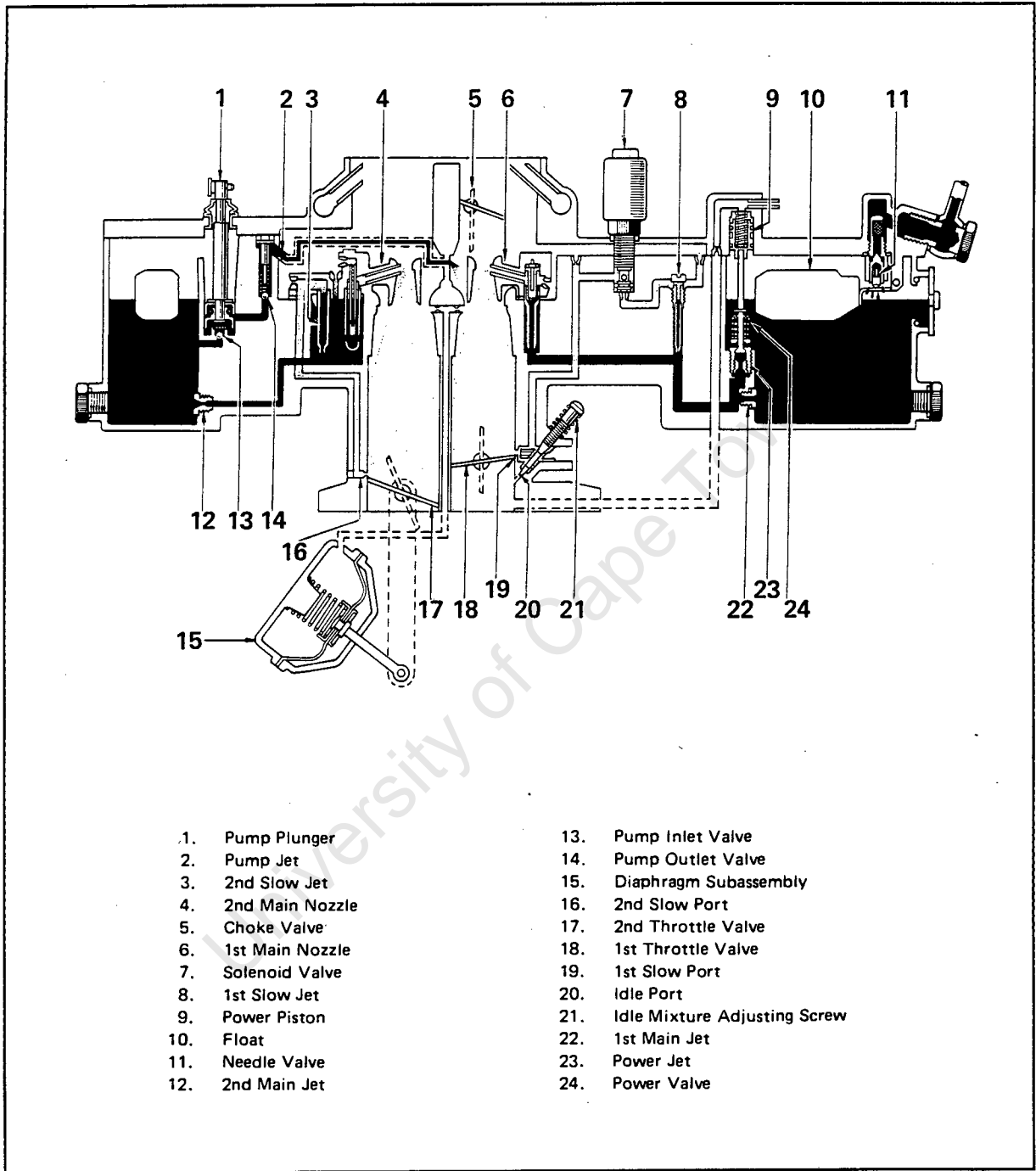


Figure A.1 Schematic layout of the downdraught twin barrel carburettor

**APPENDIX B
PROPERTIES OF TEST FUELS**

	Coastal 93	Ethanol Blend
Distillation Curve (°C)		
IBP	37.0	35.0
Recovery 10 %	56.0	52.0
20 %	65.0	58.0
30 %	73.0	63.0
40 %	82.0	67.0
50 %	90.0	89.0
60 %	100.0	104.0
70 %	109.0	115.0
80 %	121.0	129.0
90 %	139.0	155.0
FDP	184.0	190.0
Reid Vapour Pressure (kPa)	57	61
Density @ 20 °C (kg/l)	0.7243	0.7234
Alcohol Content (% v/v)	--	10
Lead Content (g/l)	0.200	0.222
Heating Value (MJ/kg)	45.3	42.8
RON	92.7	95.3
MON	83.7	85.4
Sensitivity	9.0	9.9

APPENDIX C
ENGINE TEST SEQUENCE

Test No.	Altitude (m)	Speed (rpm)	Carburation
1	0	4500	Sea-level
2	0	3500	Sea-level
3	0	2500	Sea-level
4	0	1500	Sea-level
5	1200	4500	Sea-level
6	1200	4500	Highveld
7	800	4500	Highveld
8	400	4500	Highveld
9	0	4500	Highveld
10	1200	3500	Sea-level
11	1200	3500	Highveld
12	800	3500	Highveld
13	400	3500	Highveld
14	0	3500	Highveld
15	1200	2500	Sea-level
16	1200	2500	Highveld
17	800	2500	Highveld
18	400	2500	Highveld
19	0	2500	Highveld
20	1200	1500	Sea-level
21	1200	1500	Highveld
22	800	1500	Highveld
23	400	1500	Highveld
24	0	1500	Highveld
25	800	4500	Sea-level
26	800	4500	Compensation
27	800	3500	Sea-level
28	800	3500	Compensation
29	800	2500	Sea-level
30	800	2500	Compensation
31	800	1500	Sea-level
32	800	1500	Compensation
33	400	4500	Sea-level
34	400	4500	Compensation
35	400	3500	Sea-level
36	400	3500	Compensation
37	400	2500	Sea-level
38	400	2500	Compensation
39	400	1500	Sea-level
40	400	1500	Compensation

Remarks: 0 m = 101.3 kPa
 400 m = 96.7 kPa
 800 m = 92.1 kPa
 1200 m = 87.5 kPa

**APPENDIX D
TABLES**

TABLE D.1 Summary of Test Results with the Coastal 93 Fuel

Test No.	Altitude (m)	Cell Pressure (kPa)	Speed (rpm)	Inlet Manifold Air Density (kg/m ³)	Lambda	Fuel Flowrate (g/s)	Spark Timing		Standard Timing			KLSA			Exhaust Emission	
							Standard	KLSA	Torque (Nm)	Power (kW)	BSFC (g/kWh)	Torque (Nm)	Power (kW)	BSFC (g/kWh)	CO (%)	CO ₂ (%)
1	0	101.3	4505	1.038	0.83	4.87	31	28	117	55.1	318	117	55.1	318	6.6	11.4
2	0	101.3	3504	1.058	0.84	3.74	28	25	121	44.3	303	121	44.3	303	6.0	11.7
3	0	101.3	2502	1.071	0.79	2.85	24	21	122	31.9	321	122	31.9	321	7.8	10.6
4	0	101.3	1501	1.083	0.90	1.43	15.5	7	105	16.5	313	106	16.6	310	3.4	13.2
5	1200	87.5	4504	0.896	0.78	4.52	31	41	98	45.3	359	96	44.3	367	9.3	10.1
6	1200	87.5	4502	0.896	0.83	4.22	31	38	99	45.7	332	97	44.8	339	6.8	11.3
7	800	92.1	4500	0.945	0.84	4.31	31	34	104	48.4	321	104	48.4	321	6.3	10.7
8	400	96.7	4503	0.990	0.86	4.41	31	32	109	51.0	311	109	51.0	311	5.5	12.1
9	0	101.3	4499	1.037	0.90	4.49	27	27	116	54.6	296	117	55.1	293	4.3	12.9
10	1200	87.5	3501	0.913	0.79	3.41	28	39	101	36.3	338	99	35.6	345	8.5	10.4
11	1200	87.5	3503	0.913	0.84	3.20	28	36	101	36.3	317	101	36.3	317	6.3	11.5
12	800	92.1	3499	0.963	0.85	3.32	28	32	108	39.1	305	107	38.8	308	5.8	11.8
13	400	96.7	3502	1.009	0.87	3.38	28	29	113	41.2	295	113	41.2	295	5.1	12.3
14	0	101.3	3501	1.057	0.91	3.45	28	24	119	43.6	285	120	44.0	283	3.8	13.0
15	1200	87.5	2503	0.924	0.75	2.58	24	34	102	26.2	354	102	26.2	354	9.8	9.7
16	1200	87.5	2504	0.924	0.79	2.45	24	32	103	26.5	333	103	26.5	333	7.9	10.6
17	800	92.1	2501	0.973	0.81	2.52	24	28	109	28.2	321	109	28.2	321	7.4	11.0
18	400	96.7	2501	1.021	0.82	2.59	24	24	115	29.9	312	115	29.9	312	6.6	11.6
19	0	101.3	2500	1.070	0.85	2.65	24	19	122	31.9	289	121	31.7	301	5.7	12.0
20	1200	87.5	1502	0.934	0.86	1.30	15.5	16	97	14.9	313	95	14.6	320	4.7	12.4
21	1200	87.5	1504	0.933	0.90	1.27	15.5	16	97	14.9	305	97	14.9	305	3.6	12.9
22	800	92.1	1503	0.984	0.91	1.29	15.5	12	101	15.7	297	100	15.5	300	3.2	13.2
23	400	96.7	1504	1.034	0.92	1.32	15.5	10	105	16.4	289	104	16.2	292	2.9	13.5
24	0	101.3	1508	1.081	0.84	1.37	15.5	7	108	17.0	291	105	16.5	299	2.4	13.8
25	800	92.1	4505	0.946	0.79	4.62	31	38	104	48.4	343	102	47.5	350	8.5	10.5
26	800	92.1	4503	0.946	0.83	4.38	31	35	104	48.4	325	103	47.9	329	6.5	11.5
27	800	92.1	3503	0.963	0.80	3.52	28	35	106	38.4	330	106	38.4	330	7.8	10.8
28	800	92.1	3502	0.962	0.84	3.35	28	33	107	38.8	311	107	38.8	311	6.2	11.6
29	800	92.1	2505	0.973	0.76	2.64	24	29	108	27.9	340	109	28.2	337	8.9	10.2
30	800	92.1	2504	0.971	0.79	2.59	24	28	109	28.2	331	109	28.2	331	8.1	10.6
31	800	92.1	1506	0.984	0.87	1.32	15.5	13	100	15.5	306	101	15.7	303	4.3	12.7
32	800	92.1	1505	0.983	0.90	1.32	15.5	13	101	15.7	303	101	15.7	303	3.3	13.1
33	400	96.7	4506	0.988	0.80	4.74	31	34	110	51.5	331	108	50.6	338	7.8	10.8
34	400	96.7	4504	0.991	0.83	4.58	31	33	109	51.0	323	108	50.6	326	6.6	11.4
35	400	96.7	3499	1.009	0.81	3.62	28	31	112	40.8	319	112	40.8	319	7.3	11.1
36	400	96.7	3498	1.009	0.84	3.49	28	30	112	40.8	308	112	40.8	308	6.1	11.7
37	400	96.7	2504	1.021	0.77	2.72	24	26	113	29.4	333	114	29.7	330	8.5	10.4
38	400	96.7	2501	1.020	0.79	2.70	24	25	114	29.7	328	114	29.7	328	8.0	10.6
39	400	96.7	1503	1.033	0.88	1.38	15.5	9	105	16.4	302	102	15.9	311	4.0	12.7
40	400	96.7	1505	1.033	0.90	1.37	15.5	10	105	16.4	301	104	16.2	304	3.3	13.2

TABLE D.2 Summary of Test Results with the Ethanol Blend Fuel

Test No.	Altitude (m)	Cell Pressure (kPa)	Speed (rpm)	Inlet		Fuel Flowrate (g/s)	Spark Timing		Standard Timing			KLSA			Exhaust Emission	
				Manifold Air Densit (kg/m ³)	Lambda		Standard	KLSA	Torque (Nm)	Power (kW)	BSFC (g/kWh)	Torque (Nm)	Power (kW)	BSFC (g/kWh)	CO (%)	CO ₂ (%)
1	0	101.3	4506	1.039	0.87	4.70	31	28	118	55.6	304	117	55.1	307	4.9	12.3
2	0	101.3	3503	1.059	0.93	3.41	28	26	121	44.3	277	121	44.3	277	2.9	13.4
3	0	101.3	2505	1.072	0.86	2.58	24	23	123	32.2	289	123	32.2	289	4.9	12.2
4	0	101.3	1503	1.083	0.92	1.30	15.5	13	112	17.6	266	112	17.6	266	1.6	13.6
5	1200	87.5	4500	0.894	0.87	4.30	31	40	97	44.8	345	95	43.9	353	7.1	11.0
6	1200	87.5	4502	0.897	0.87	4.01	31	37	96	44.4	325	95	43.9	329	4.9	12.2
7	800	92.1	4502	0.943	0.90	4.00	31	35	102	47.5	303	102	47.5	303	3.9	12.8
8	400	96.7	4501	0.989	0.92	4.12	31	32	107	50.1	296	107	50.1	296	3.0	13.4
9	0	101.3	4506	1.036	0.97	4.22	31	28	113	53.2	286	113	53.2	286	1.6	13.6
10	1200	87.5	3504	0.914	0.87	3.05	28	39	98	35.2	312	96	34.5	318	4.9	12.0
11	1200	87.5	3503	0.912	0.93	2.86	28	36	98	35.2	292	97	34.8	295	2.8	13.4
12	800	92.1	3498	0.961	0.96	2.90	28	32	106	38.4	272	106	38.4	272	1.7	13.5
13	400	96.7	3503	1.007	0.97	3.00	28	29	112	40.8	265	112	40.8	265	1.6	13.6
14	0	101.3	3506	1.057	1.00	3.16	28	26	119	43.6	261	118	43.2	263	1.3	13.7
15	1200	87.5	2501	0.925	0.80	2.46	24	35	105	27.0	328	101	25.9	341	7.5	10.6
16	1200	87.5	2503	0.926	0.86	2.29	24	31	105	27.0	305	103	26.5	311	4.9	12.2
17	800	92.1	2501	0.971	0.87	2.29	24	28	110	28.5	293	109	28.2	293	4.7	12.3
18	400	96.7	2502	1.021	0.89	2.33	24	25	115	29.9	281	115	29.9	281	4.3	12.4
19	0	101.3	2503	1.070	0.91	2.44	24	22	122	31.9	275	122	31.9	275	3.5	13.0
20	1200	87.5	1504	0.933	0.94	1.18	15.5	21	95	14.6	290	97	14.9	284	2.6	13.0
21	1200	87.5	1506	0.933	0.97	1.15	15.5	22	95	14.6	283	94	14.5	286	1.7	13.6
22	800	92.1	1504	0.984	0.98	1.19	15.5	20	100	15.5	276	99	15.4	279	1.6	13.7
23	400	96.7	1502	1.030	0.99	1.21	15.5	19	104	16.2	268	104	16.2	268	1.4	13.7
24	0	101.3	1502	1.081	1.00	1.26	15.5	15	107	16.8	270	107	16.8	270	1.3	13.7
25	800	92.1	4505	0.945	0.83	4.34	31	37	103	47.9	326	102	47.5	329	6.7	11.3
26	800	92.1	4503	0.946	0.87	4.17	31	35	103	47.9	313	102	47.5	316	4.9	12.2
27	800	92.1	3505	0.960	0.89	3.12	28	34	105	38.0	295	104	37.6	298	4.2	12.6
28	800	92.1	3504	0.960	0.93	2.98	28	33	104	37.6	285	104	37.6	285	2.8	13.5
29	800	92.1	2503	0.973	0.81	2.46	24	29	107	27.7	320	107	27.7	320	7.1	10.9
30	800	92.1	2505	0.974	0.86	2.32	24	30	108	27.9	298	108	27.9	298	4.8	12.2
31	800	92.1	1504	0.982	0.95	1.22	15.5	19	100	15.5	283	100	15.5	283	1.9	13.5
32	800	92.1	1502	0.983	0.97	1.18	15.5	21	100	15.5	275	99	15.3	278	1.6	13.5
33	400	96.7	4503	0.992	0.85	4.46	31	34	110	51.5	311	108	50.6	317	5.7	11.8
34	400	96.7	4502	0.990	0.87	4.35	31	33	108	50.6	310	106	49.6	316	4.8	12.2
35	400	96.7	3504	1.008	0.91	3.21	28	32	111	40.4	286	109	39.7	291	3.5	13.0
36	400	96.7	3503	1.008	0.93	3.11	28	32	109	39.7	282	109	39.7	282	2.8	13.4
37	400	96.7	2504	1.022	0.82	2.54	24	28	113	29.4	311	113	29.4	311	6.8	11.1
38	400	96.7	2505	1.021	0.86	2.42	24	28	114	29.7	294	113	29.4	297	4.9	12.2
39	400	96.7	1505	1.032	0.96	1.22	15.5	18	103	16.1	274	104	16.2	271	1.7	13.5
40	400	96.7	1503	1.032	0.97	1.21	15.5	19	104	16.2	269	103	16.1	272	1.5	13.6

APPENDIX E
FIGURES

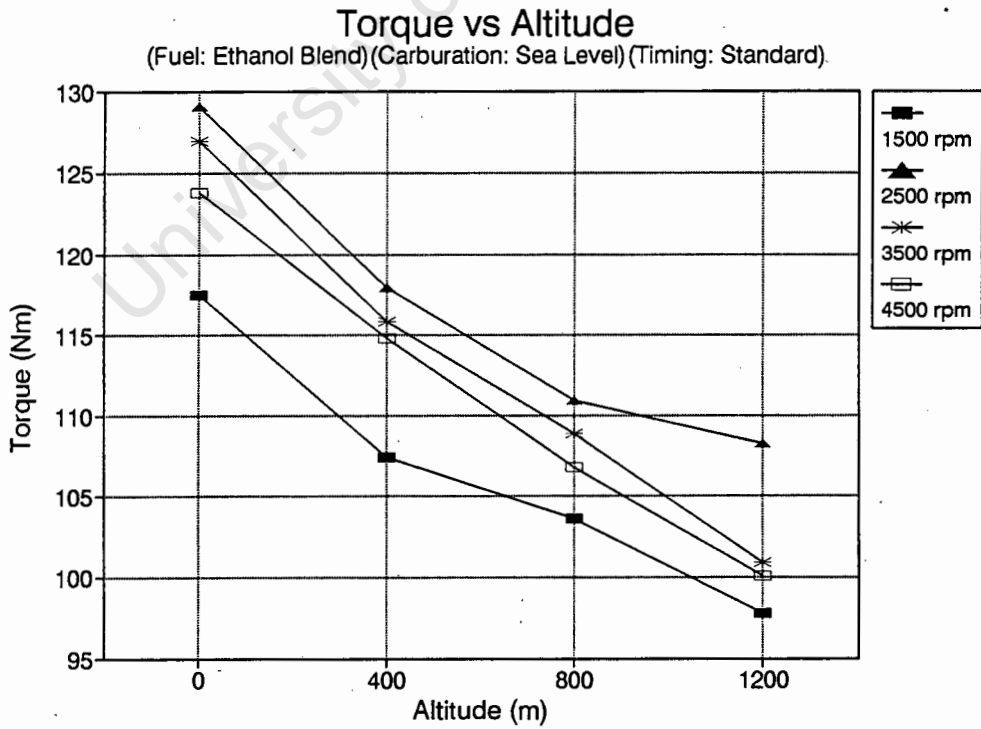
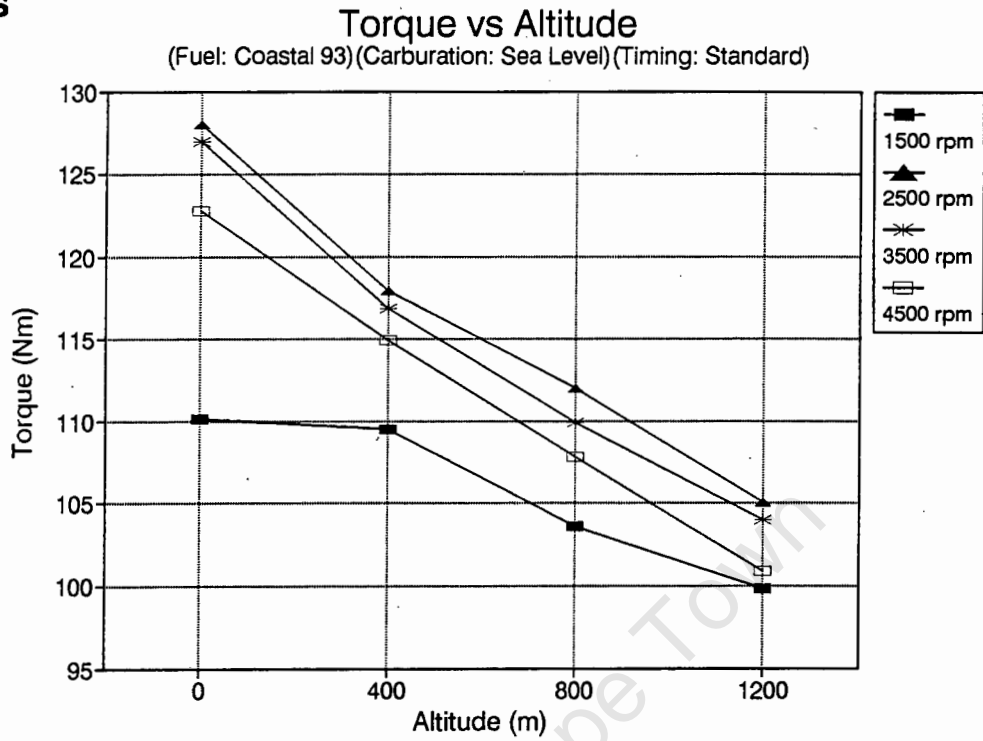


Figure E.1 Effect of altitude on standard timing torque with sea-level carburation setting

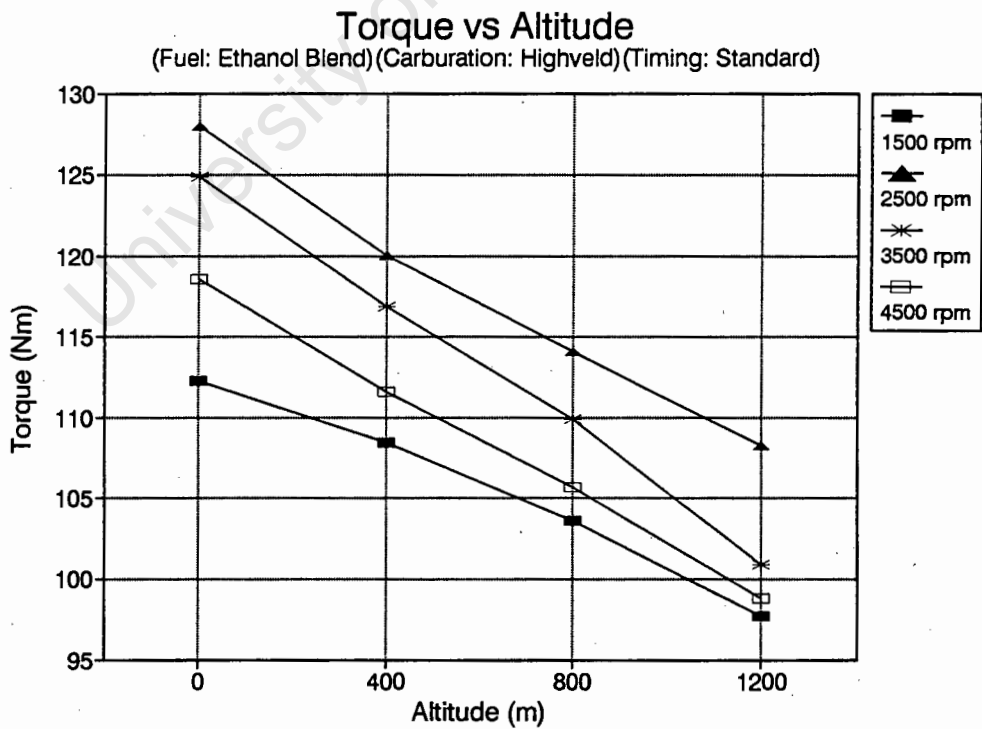
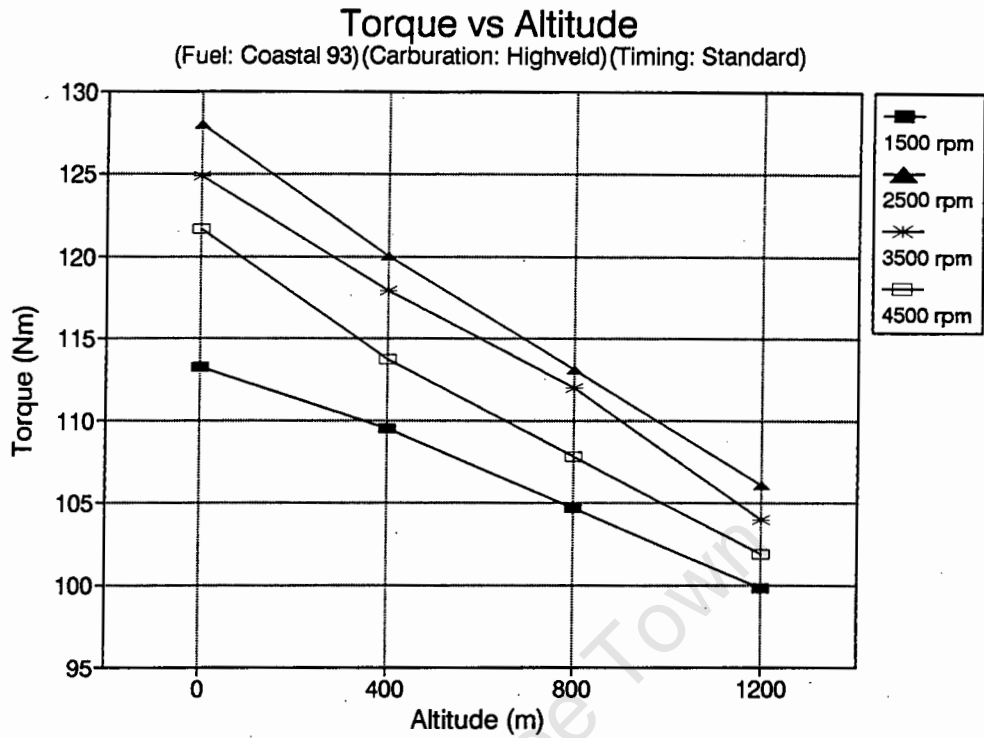


Figure E.2 Effect of altitude on standard timing torque with Highveld carburation setting

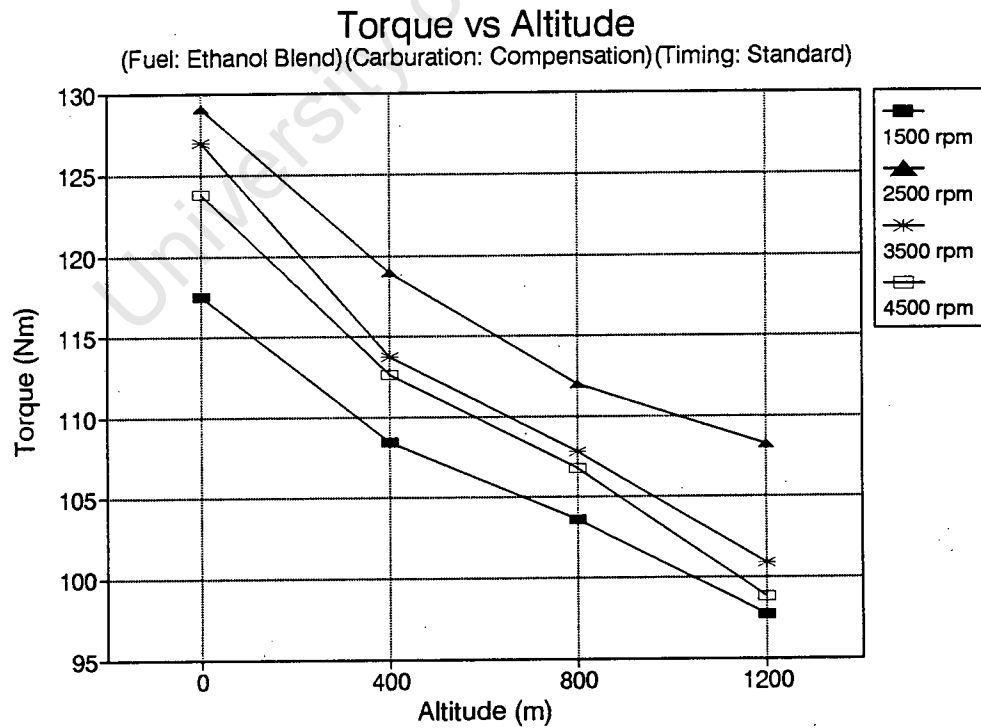
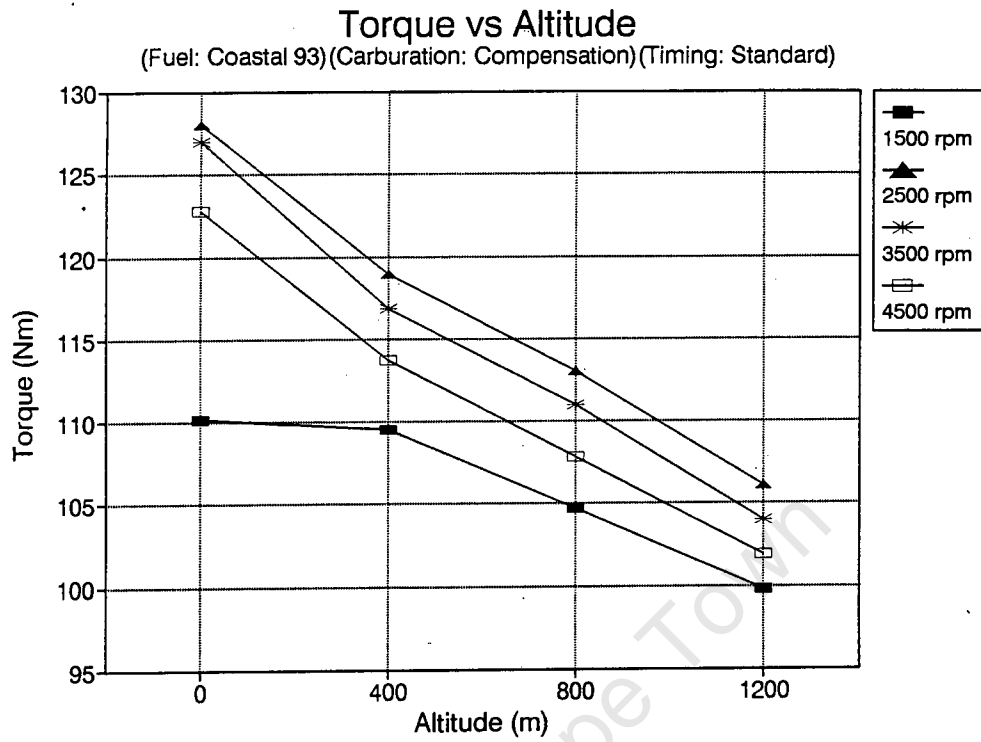


Figure E.3 Effect of altitude on standard timing torque with altitude-compensation carburation

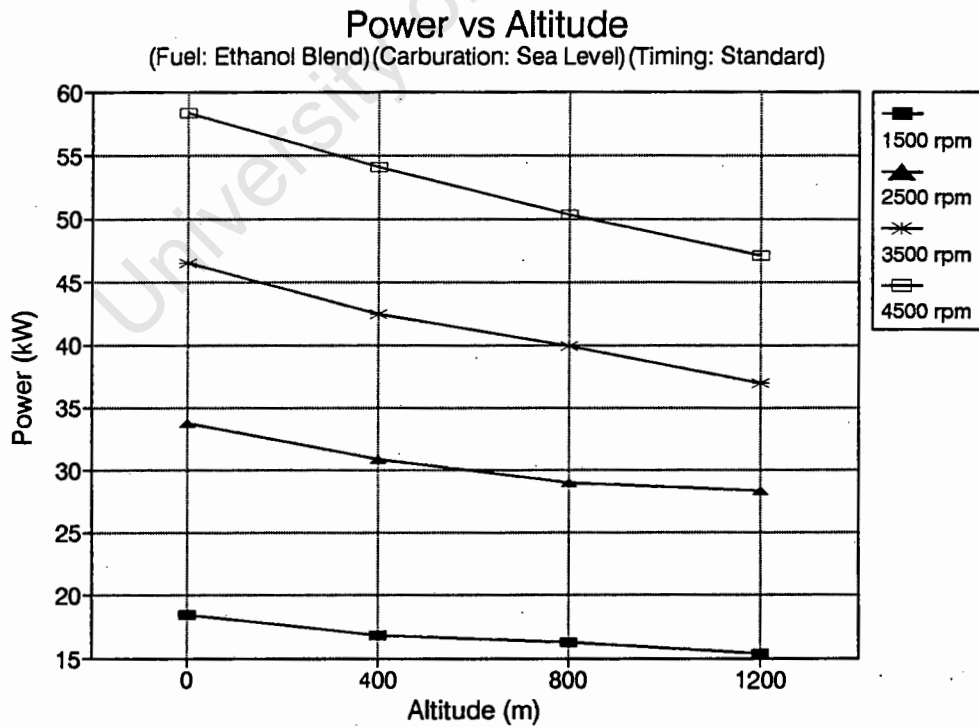
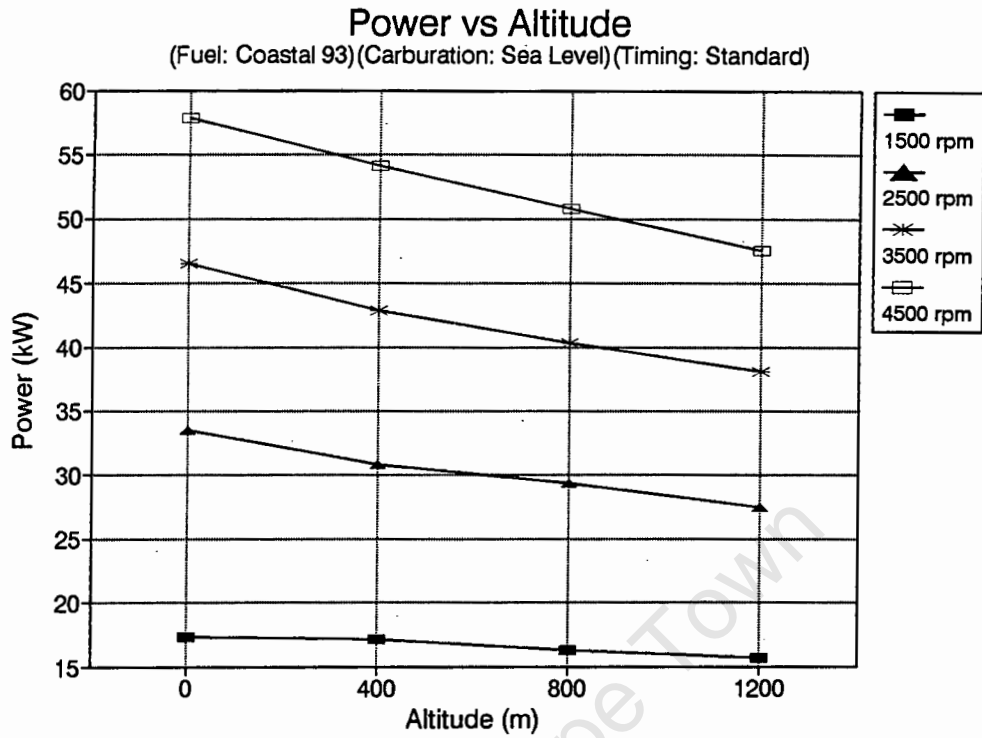


Figure E.4

Effect of altitude on engine power with sea-level carburation setting

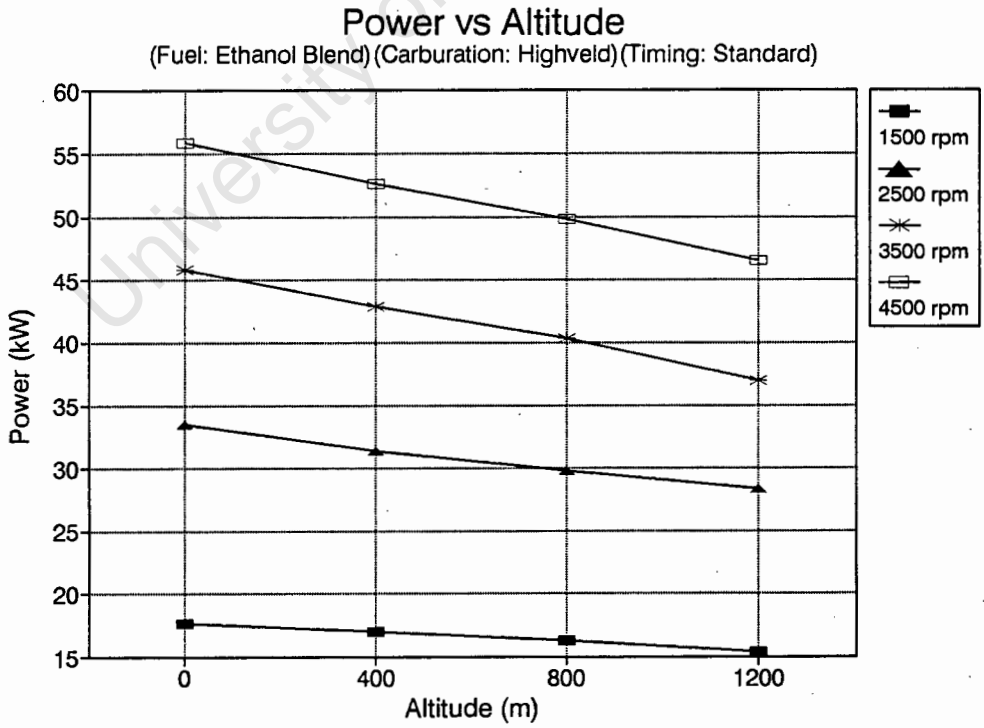
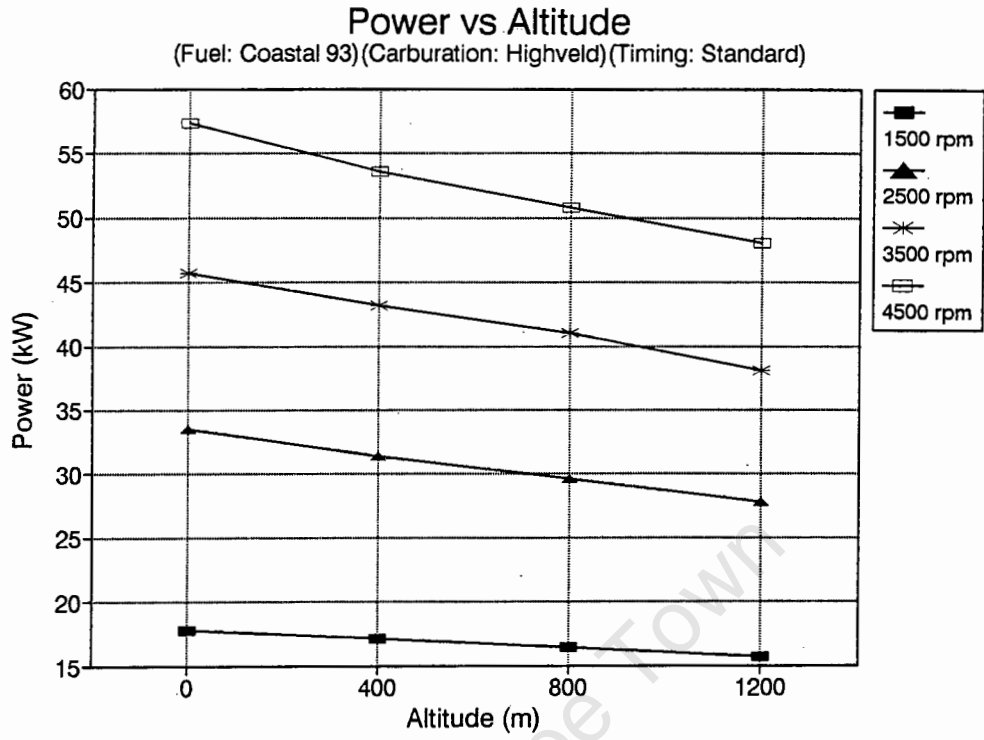


Figure E.5 Effect of altitude on engine power with Highveld carburation setting

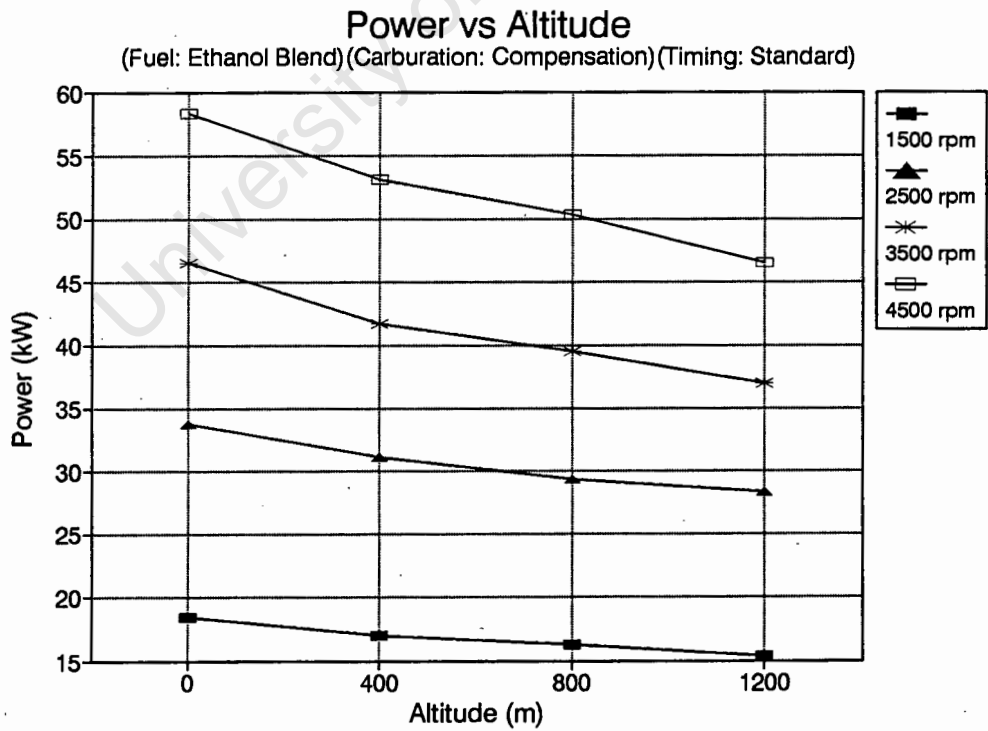
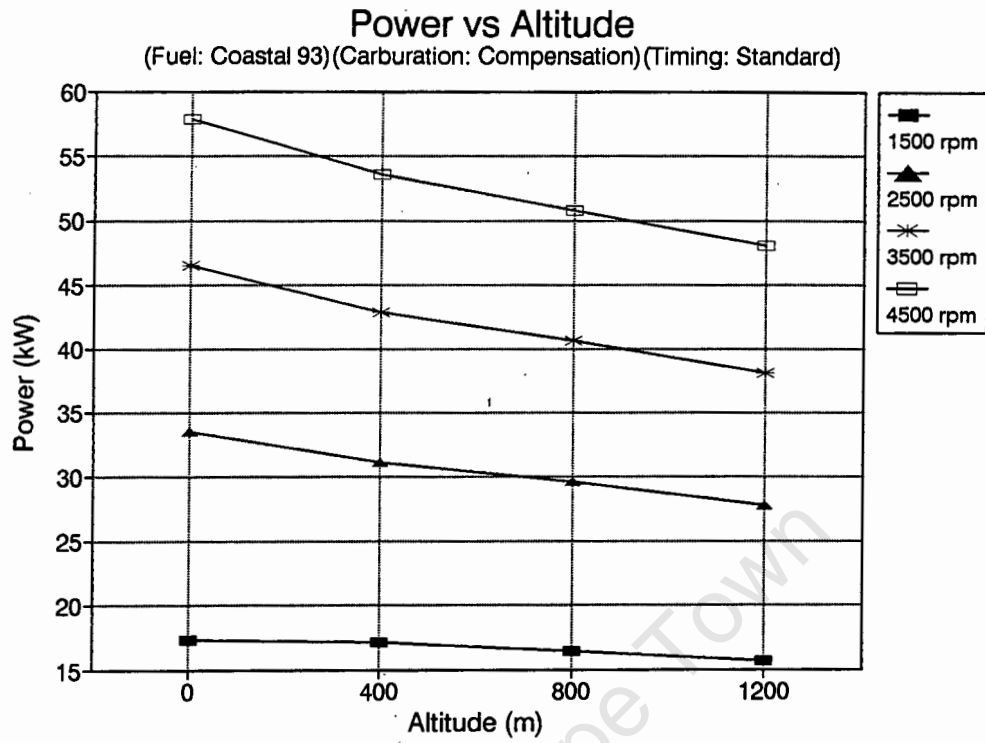


Figure E.6 Effect of altitude on engine power with altitude-compensation carburation

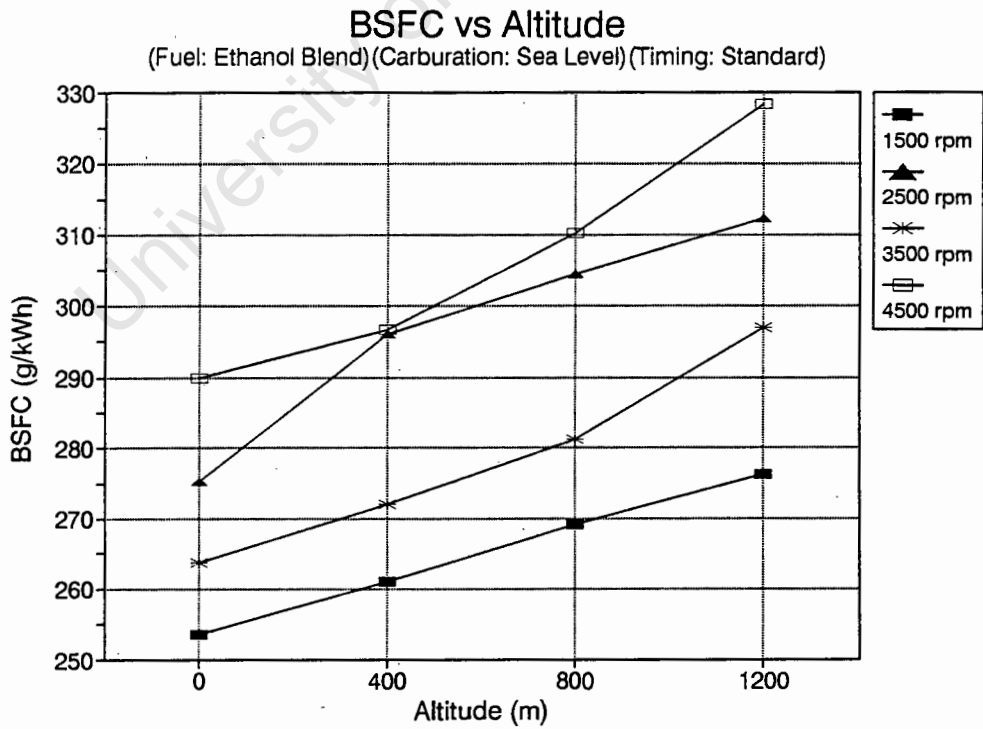
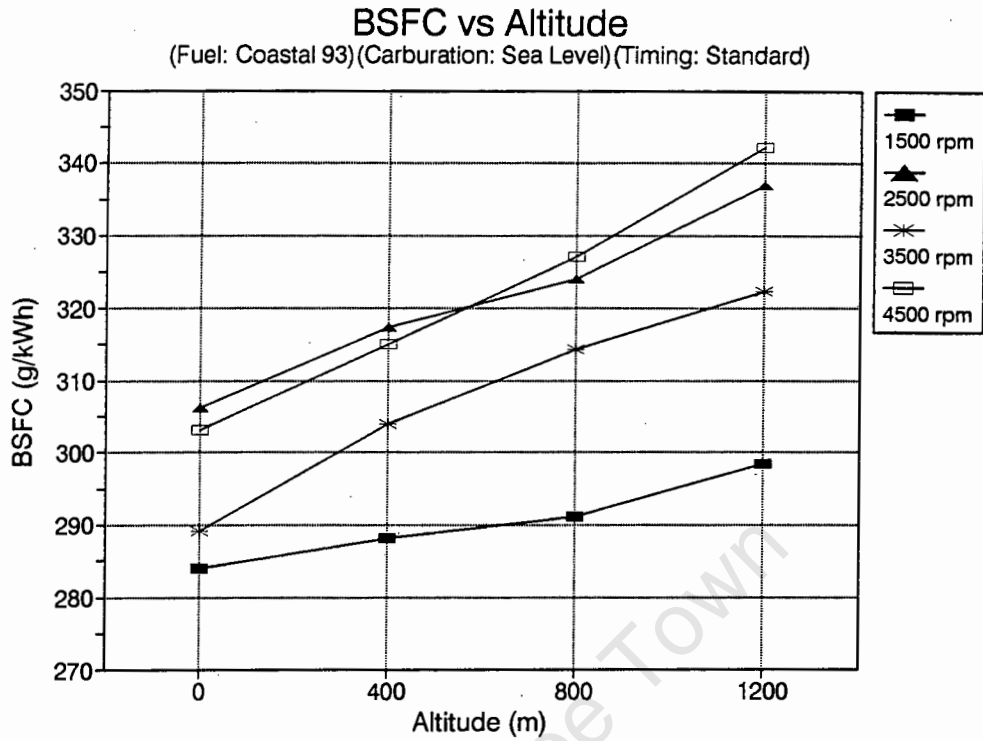


Figure E.7 Effect of altitude on bsfc with sea-level carburation setting

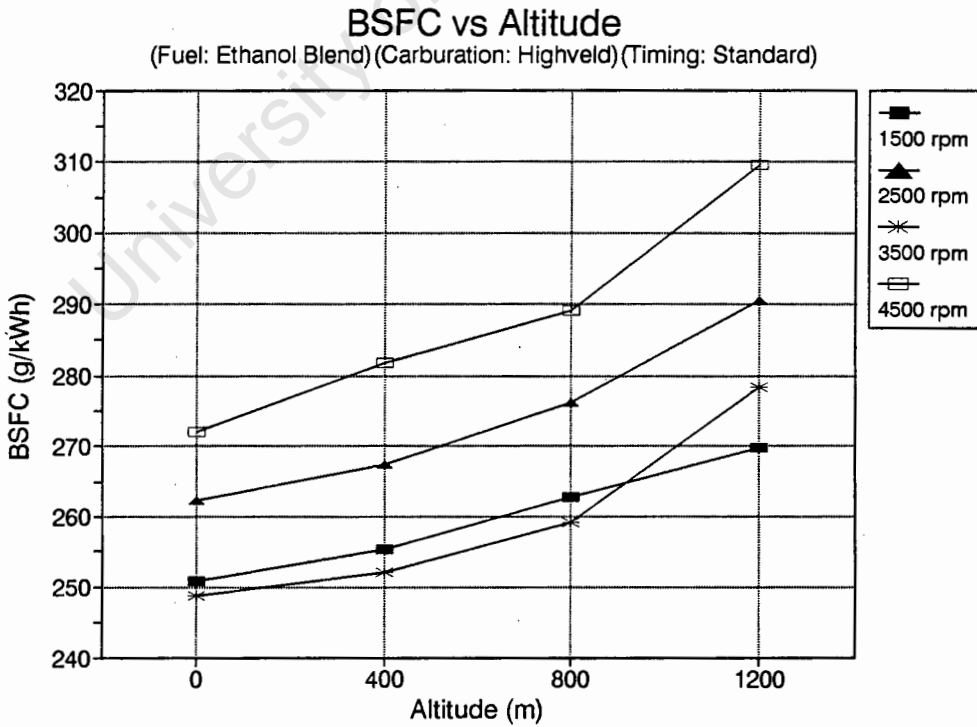
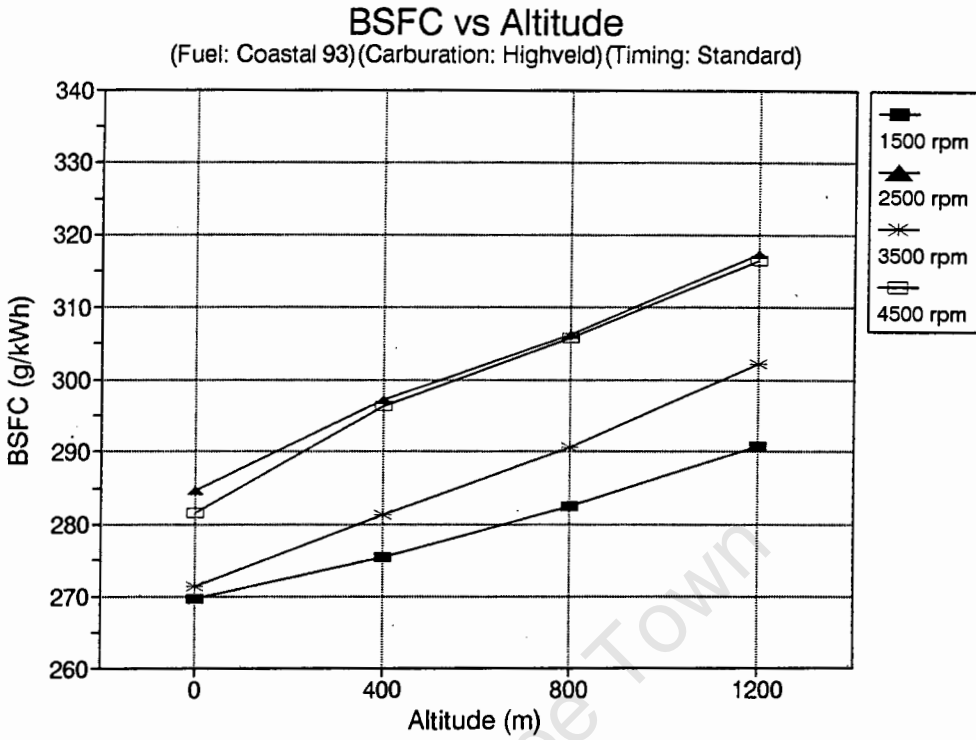


Figure E.8 Effect of altitude on bsfc with Highveld carburation setting

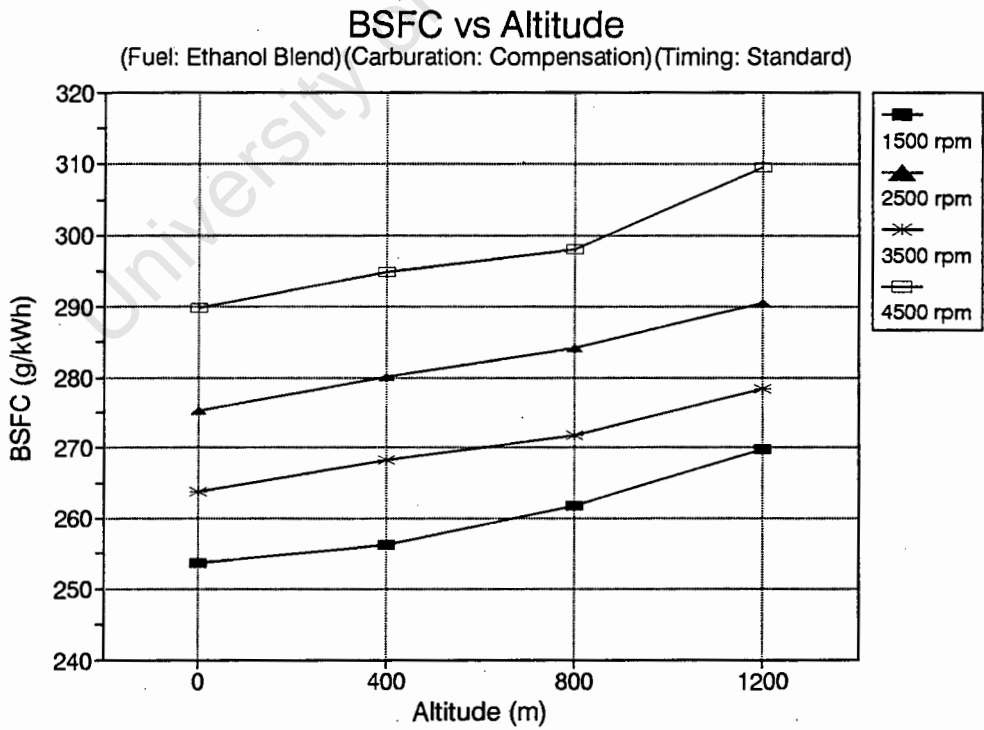
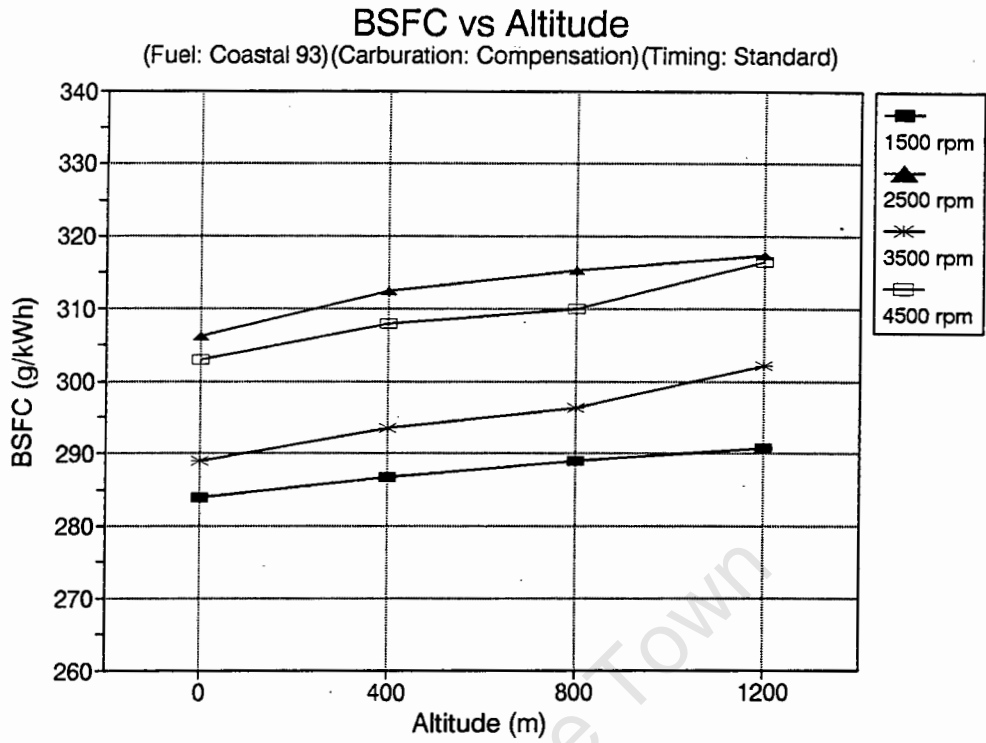


Figure E.9 Effect of altitude on bsfc with altitude-compensation carburation

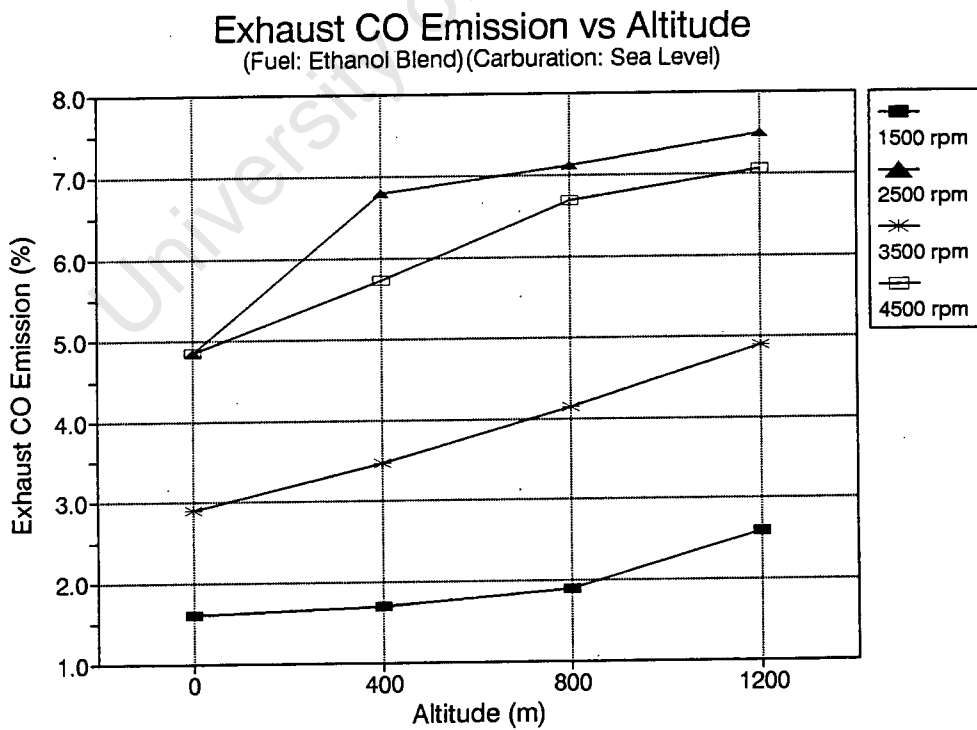
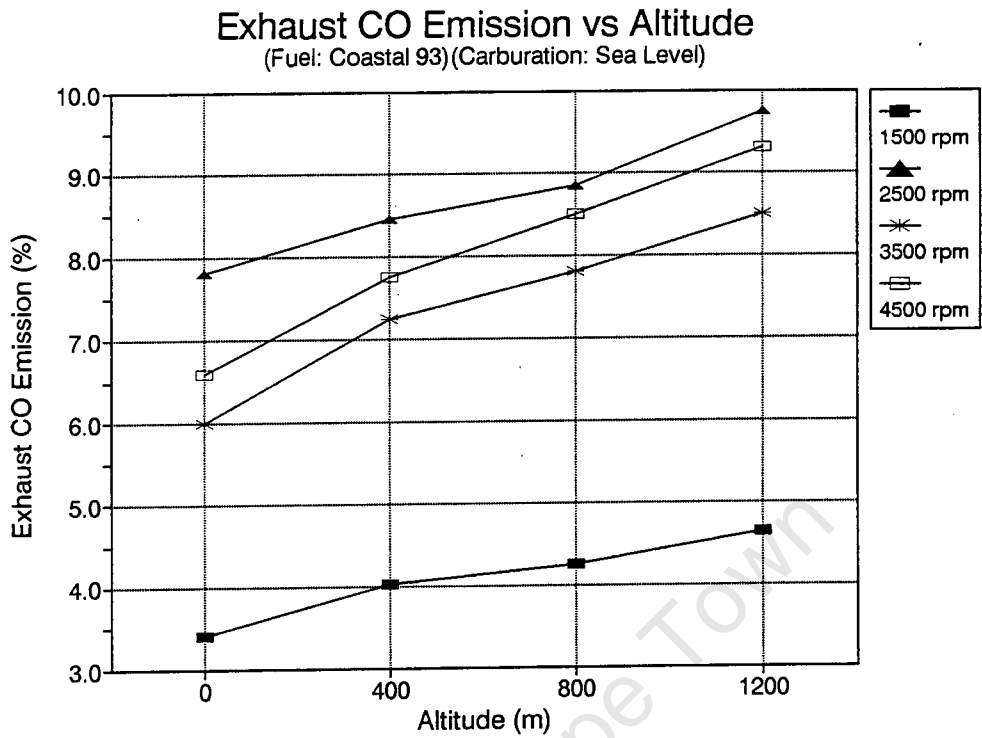


Figure E.10 Effect of altitude on exhaust CO emission with sea-level carburation setting

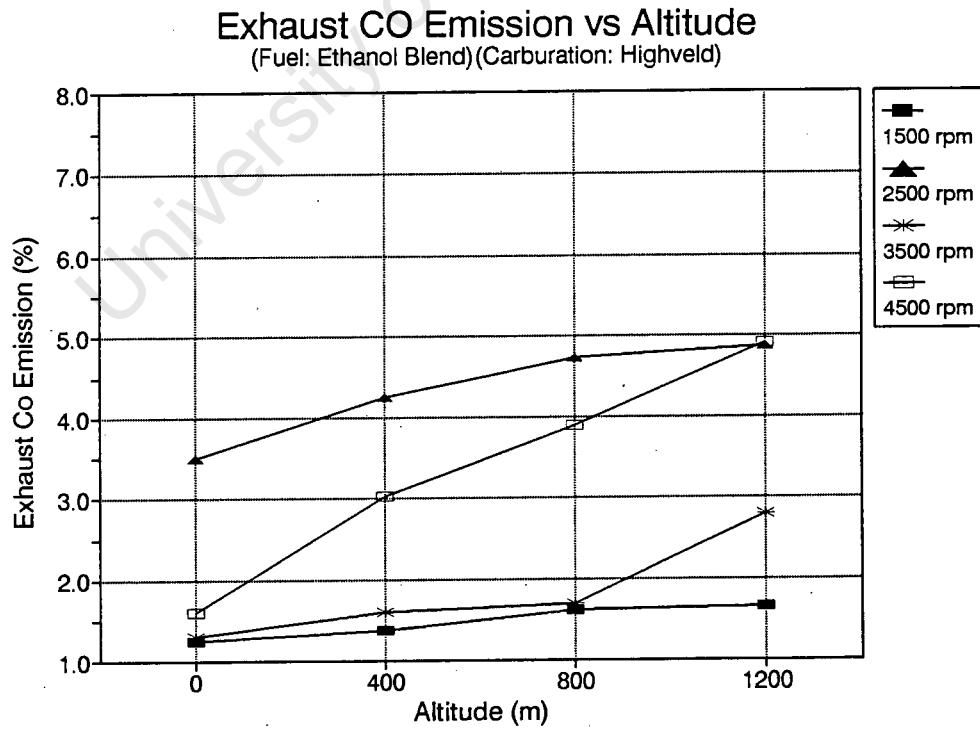
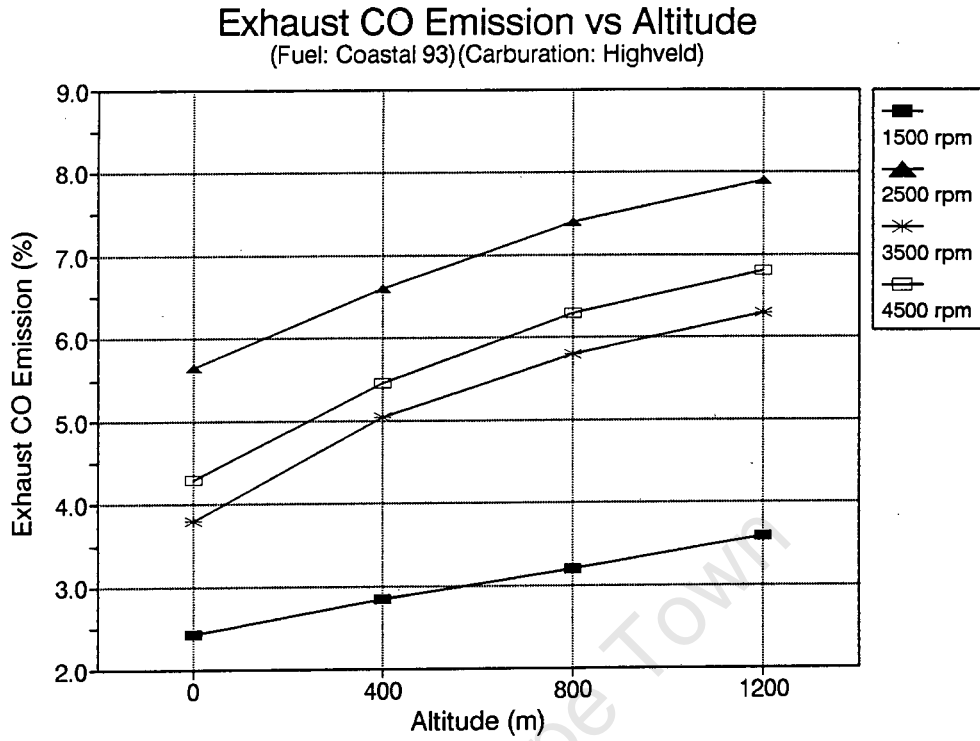


Figure E.11 Effect of altitude on exhaust CO emission with Highveld carburation setting

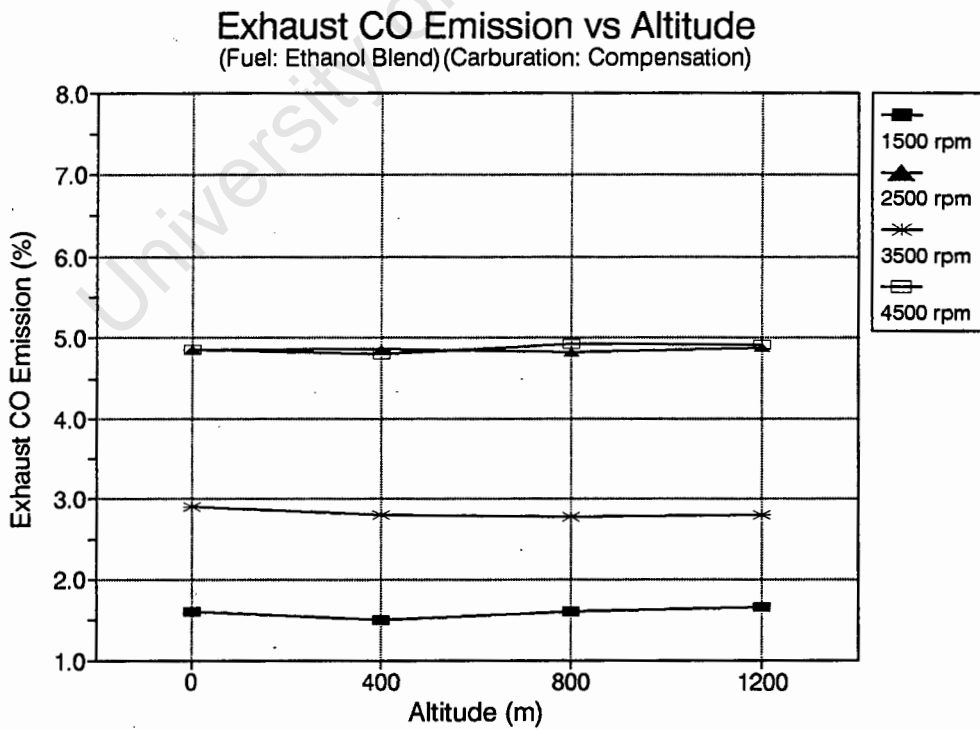
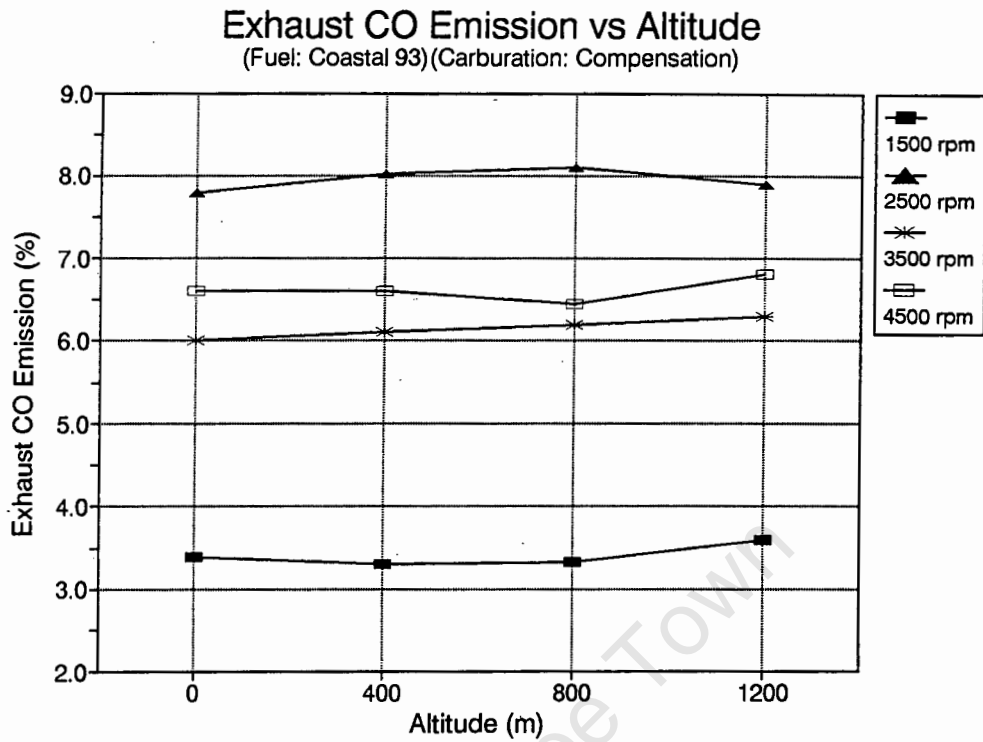


Figure E.12 Effect of altitude on exhaust CO emission with altitude-compensation carburation

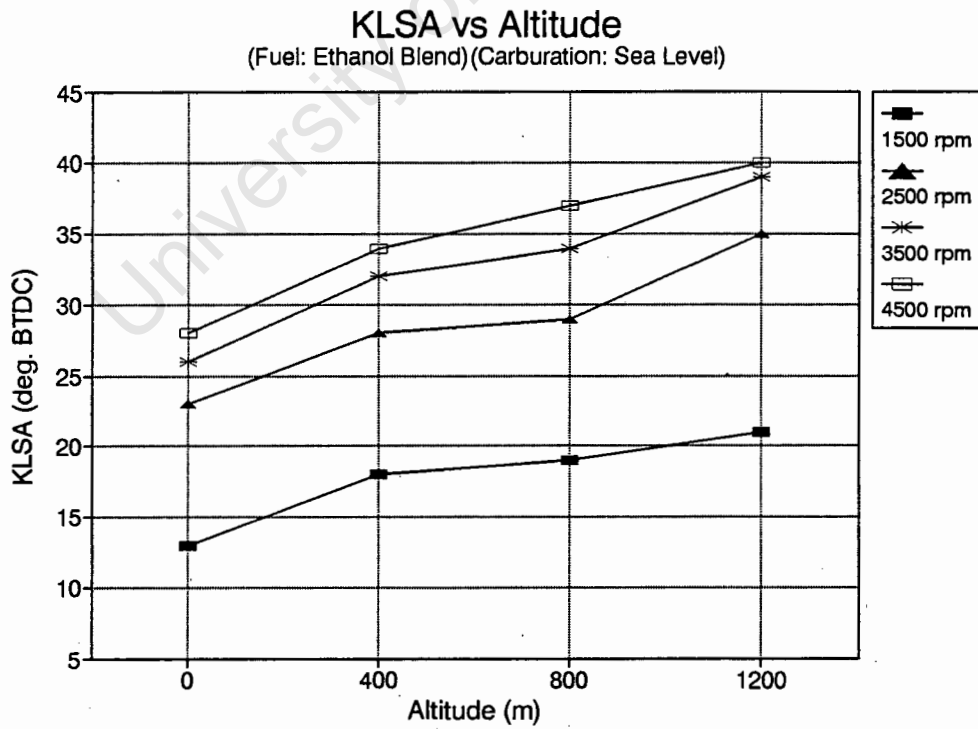
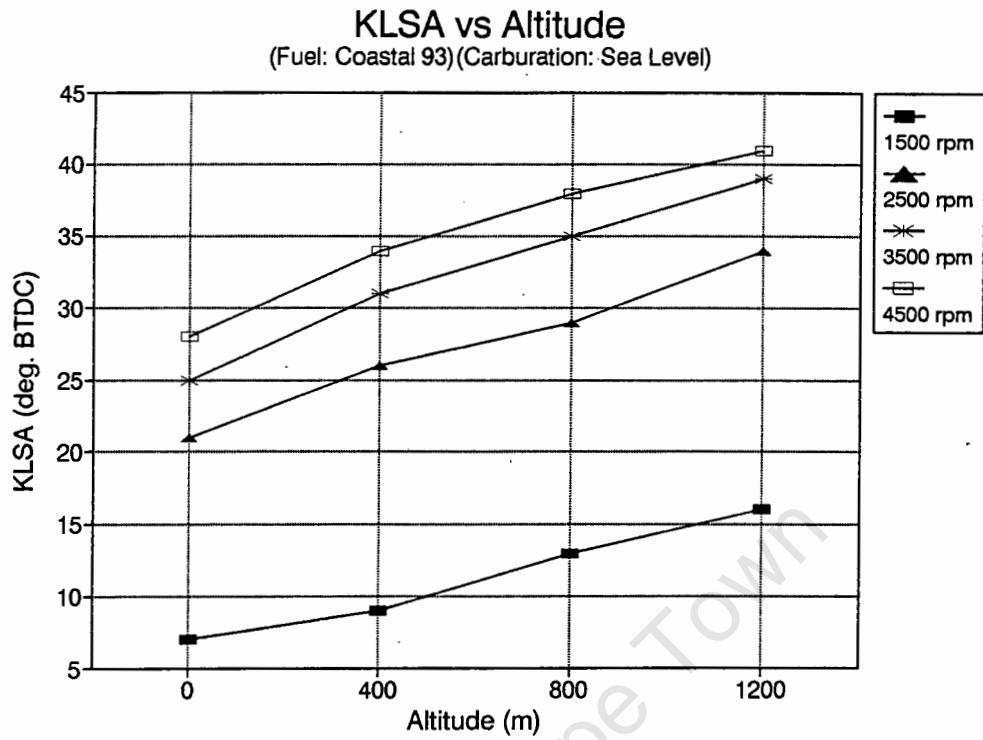


Figure E.13 Effect of altitude on KLSA with sea-level carburation setting

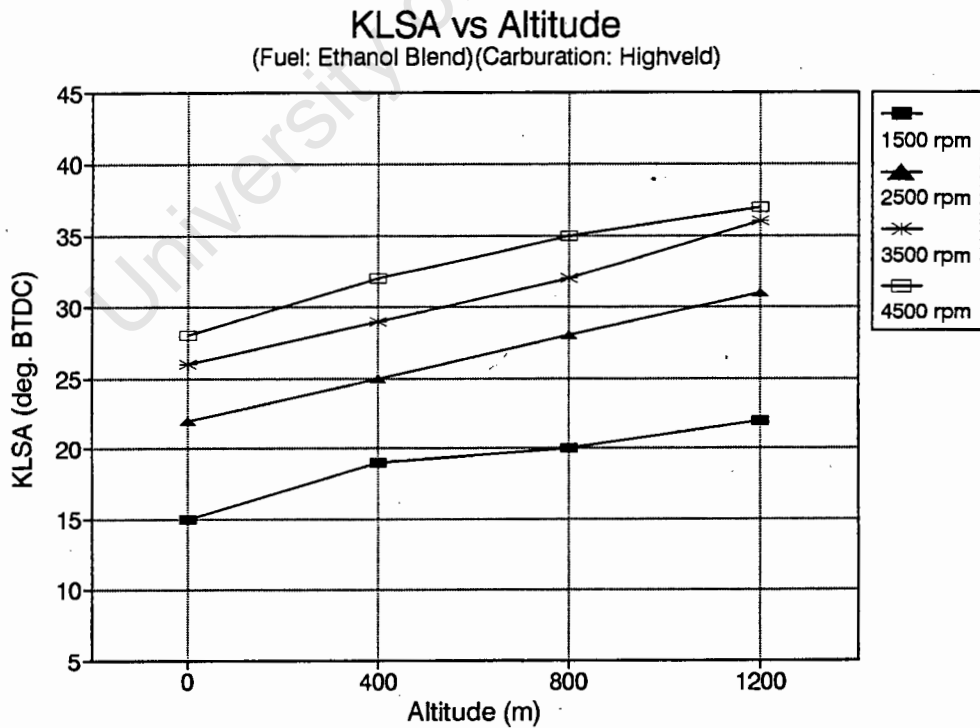
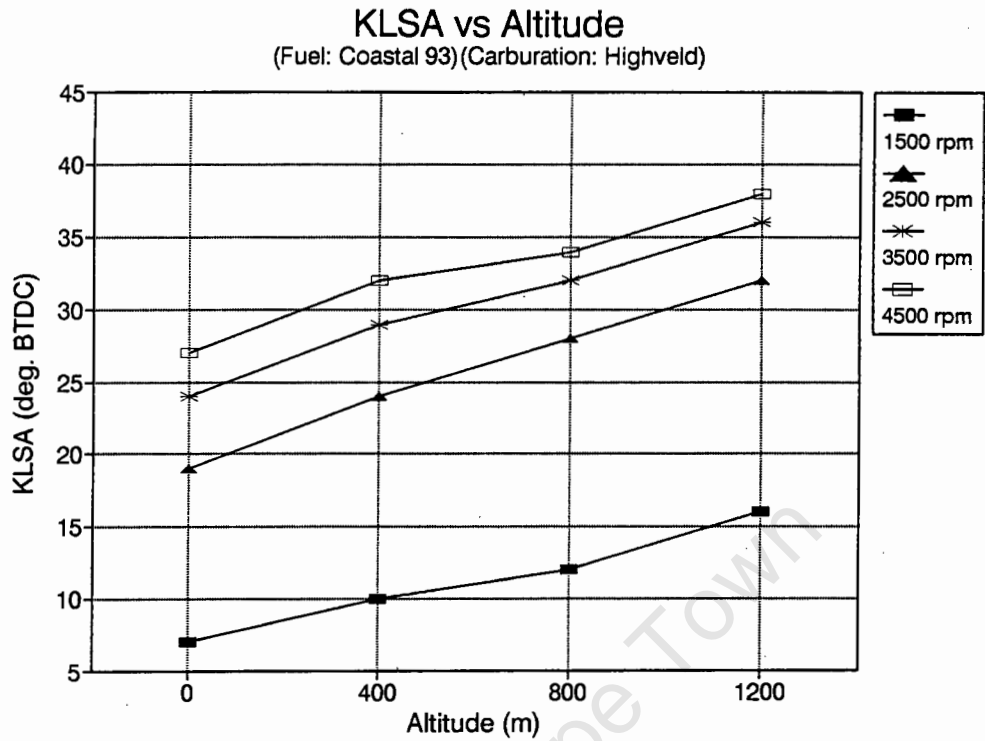


Figure E.14 Effect of altitude on KLSA with Highveld carburation setting

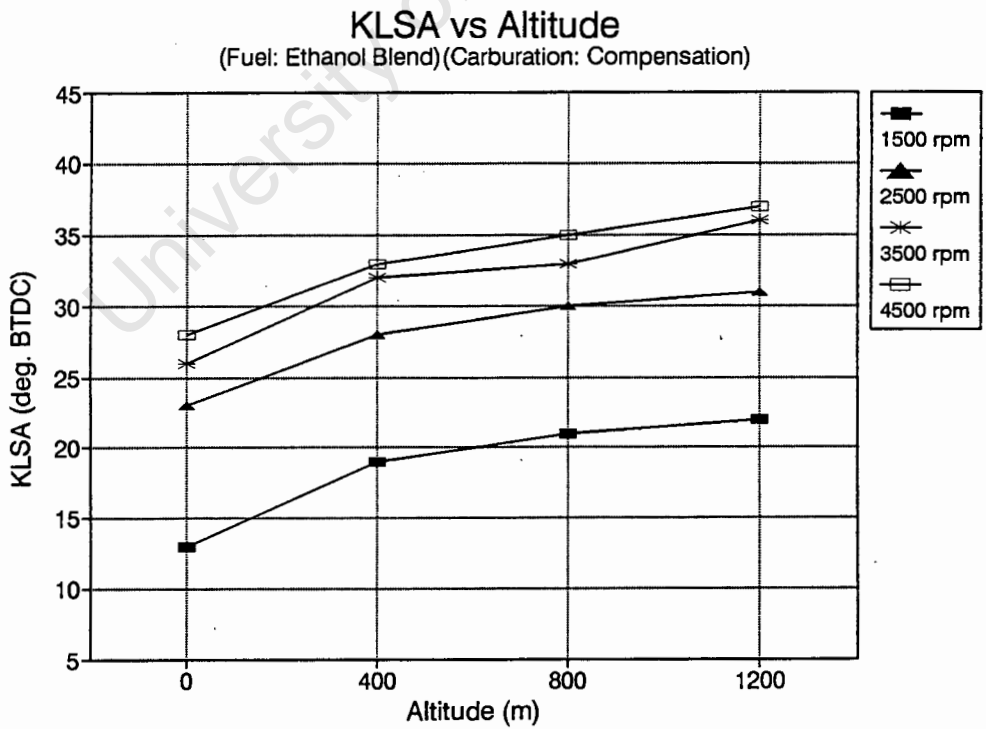
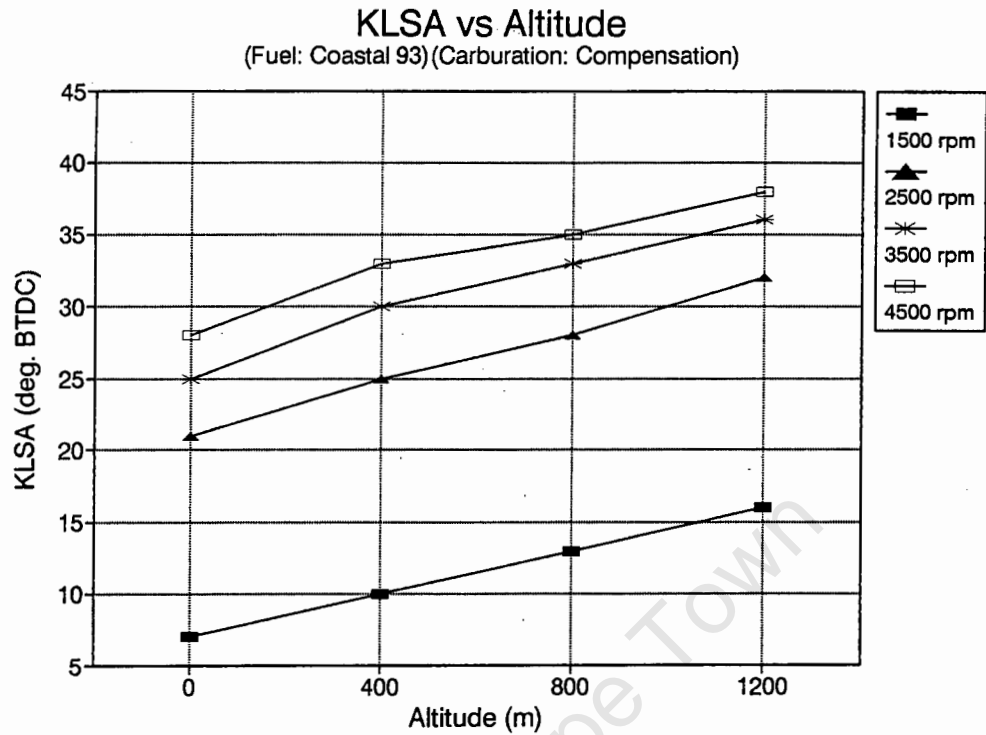


Figure E.15 Effect of altitude on KLSA with altitude-compensation carburation

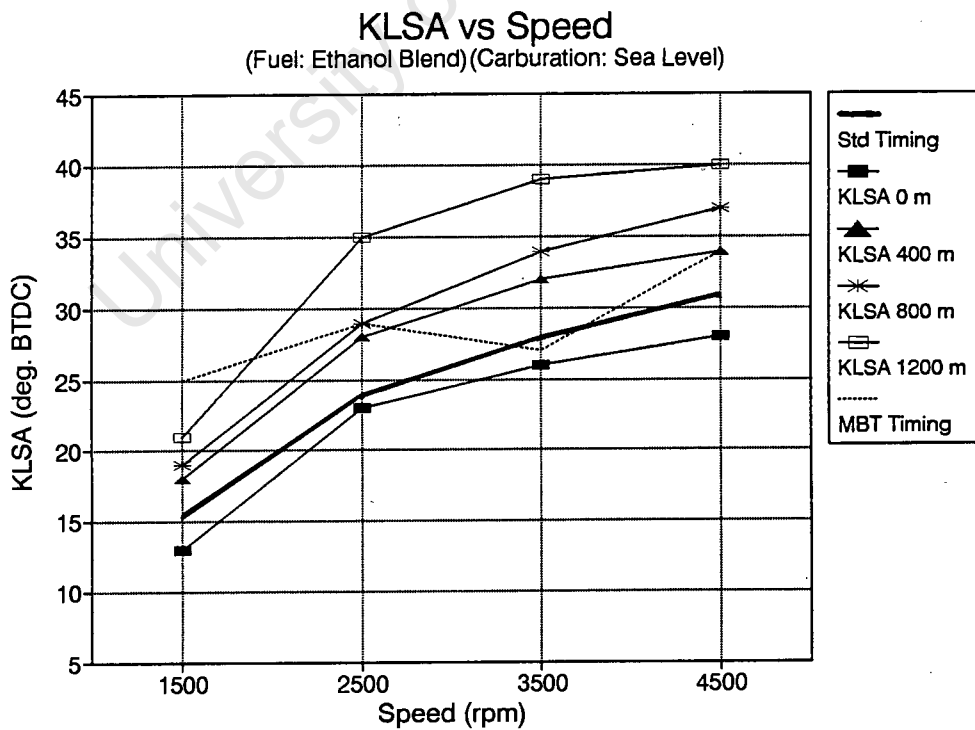
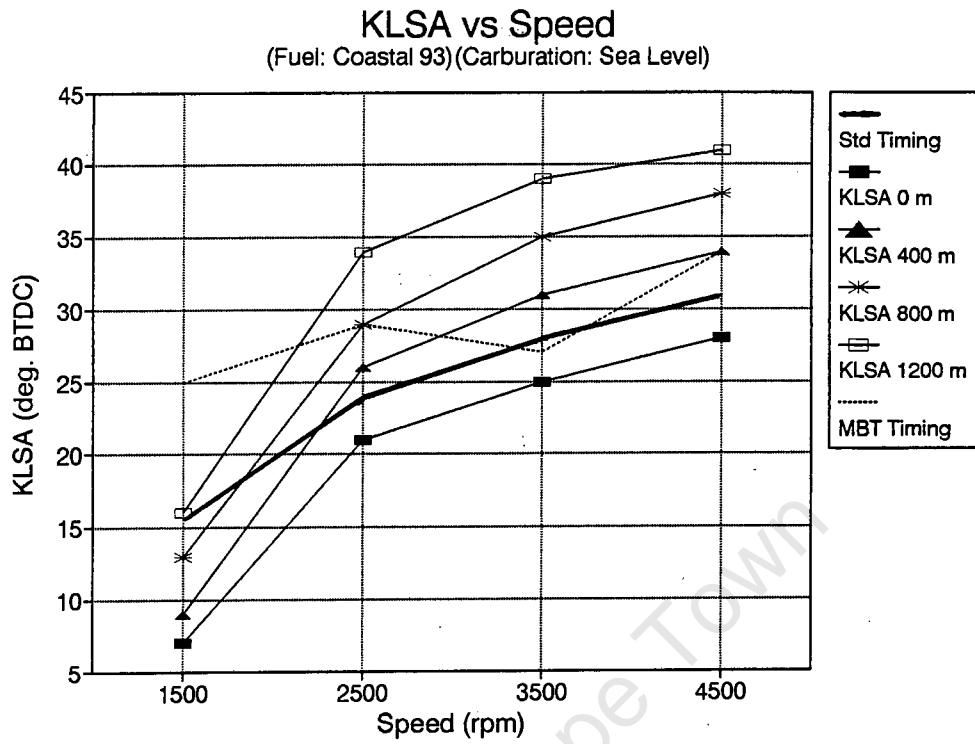


Figure E.16 Relationship of KLSA and engine speed at various altitudes with sea-level carburation setting

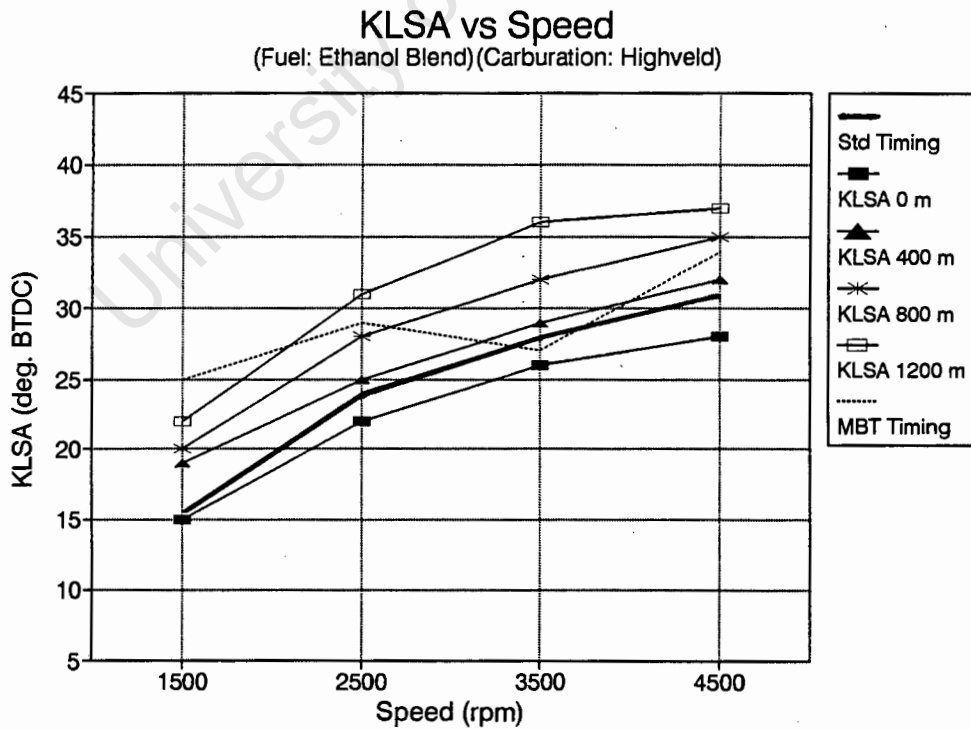
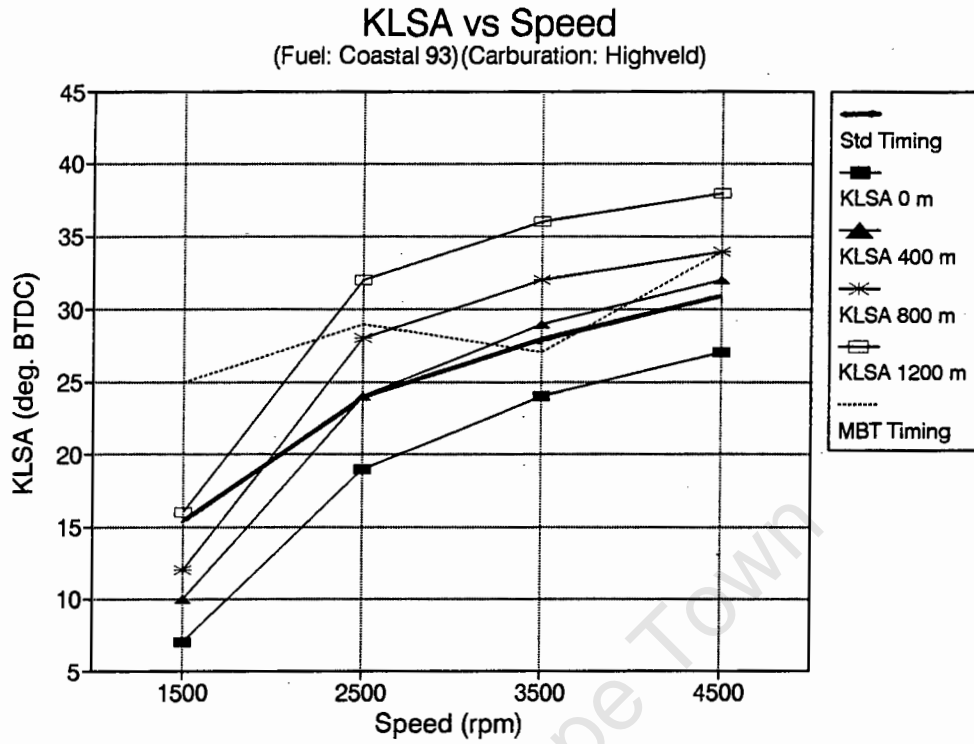


Figure E.17 Relationship of KLSA and engine speed at various altitudes with Highveld carburation setting

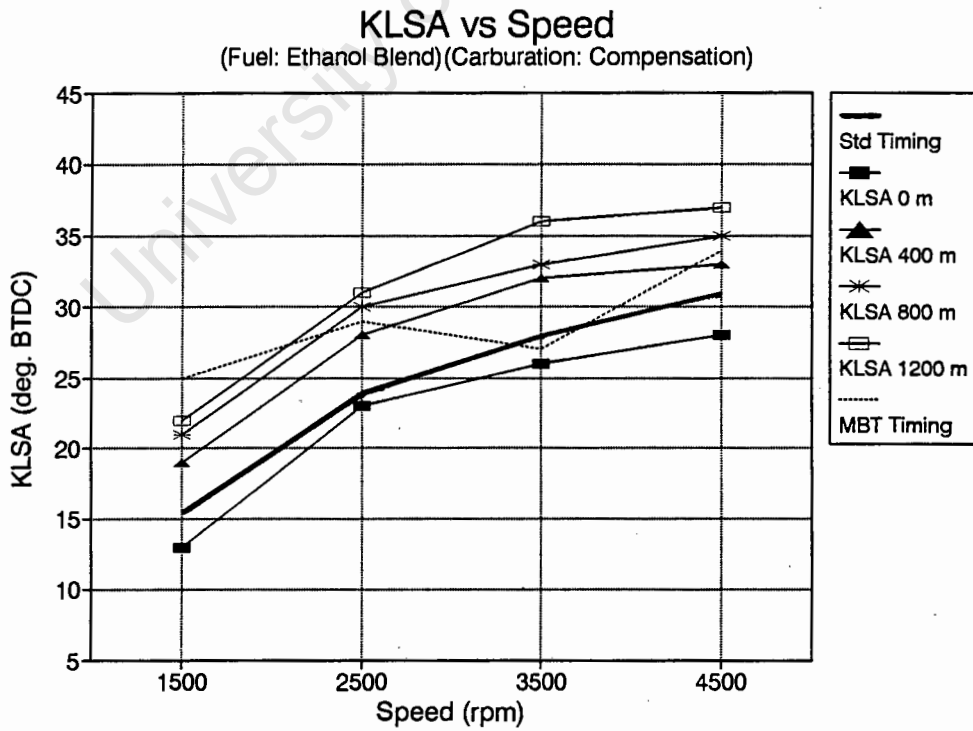
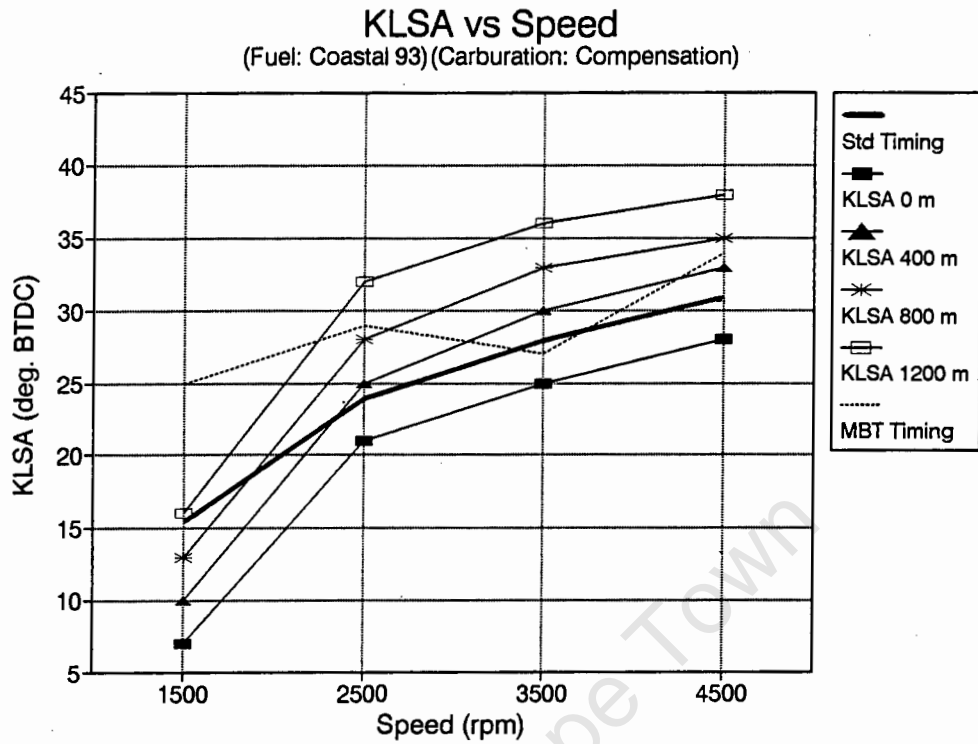
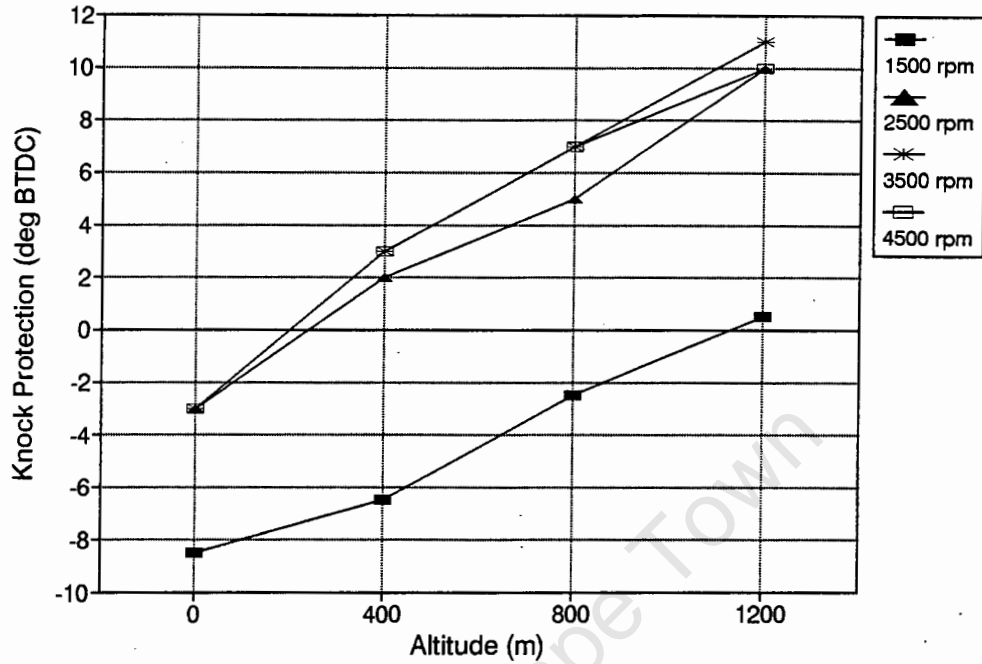


Figure E.18 Relationship of KLSA and engine speed at various altitudes with altitude-compensation carburation

Degree of Knock Protection vs Altitude

(Fuel: Coastal 93)(Carburation: Sea Level)(Timing: KLSA)



Degree of Knock Protection vs Altitude

(Fuel: Ethanol Blend)(Carburation: Sea Level)(Timing: KLSA)

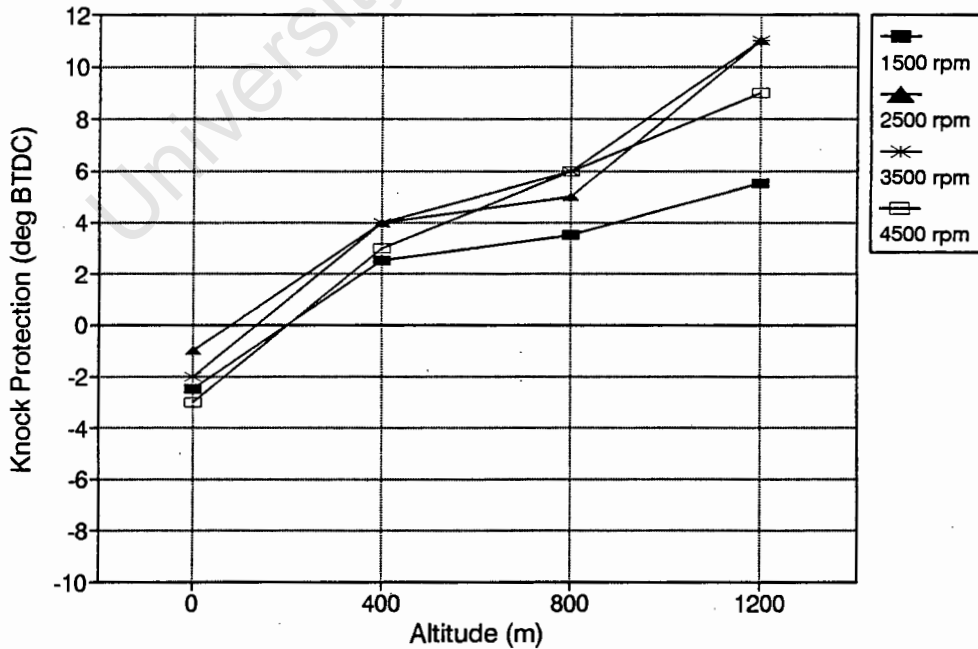
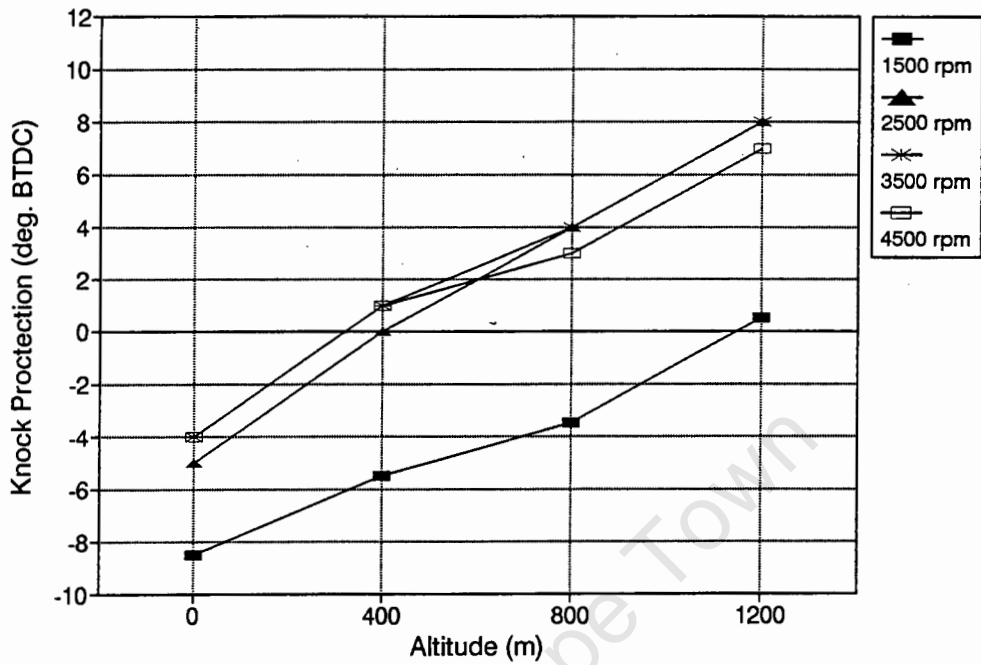


Figure E.19 Effect of altitude on engine knock protection with sea-level carburation setting

Degree of Knock Protection vs Altitude

(Fuel: Coastal 93)(Carburation: Highveld)(Timing: KLSA)



Degree of Knock Protection vs Altitude

(Fuel: Ethanol Blend)(Carburation: Highveld)(Timing: KLSA)

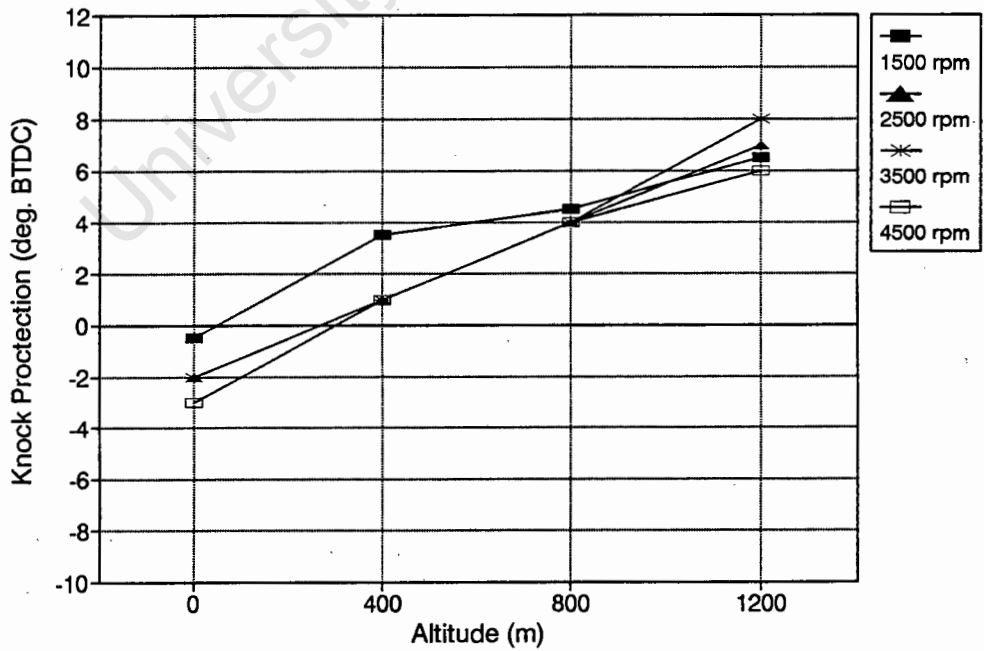


Figure E.20

Effect of altitude on engine knock protection with Highveld carburation setting

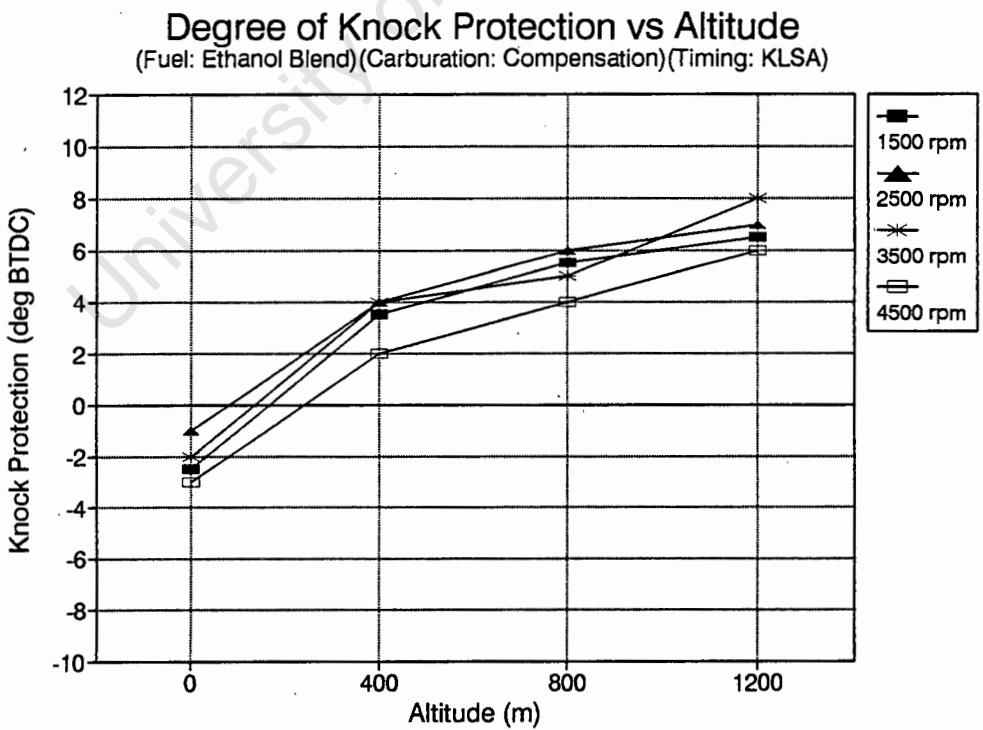
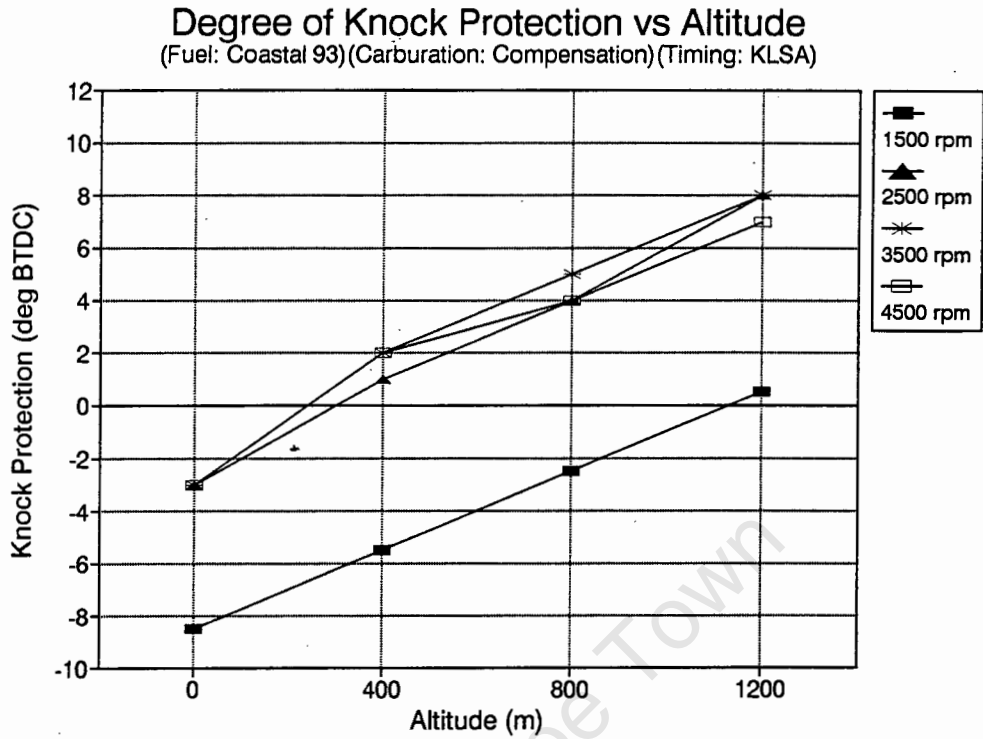


Figure E.21 Effect of altitude on engine knock protection with altitude-compensation carburation

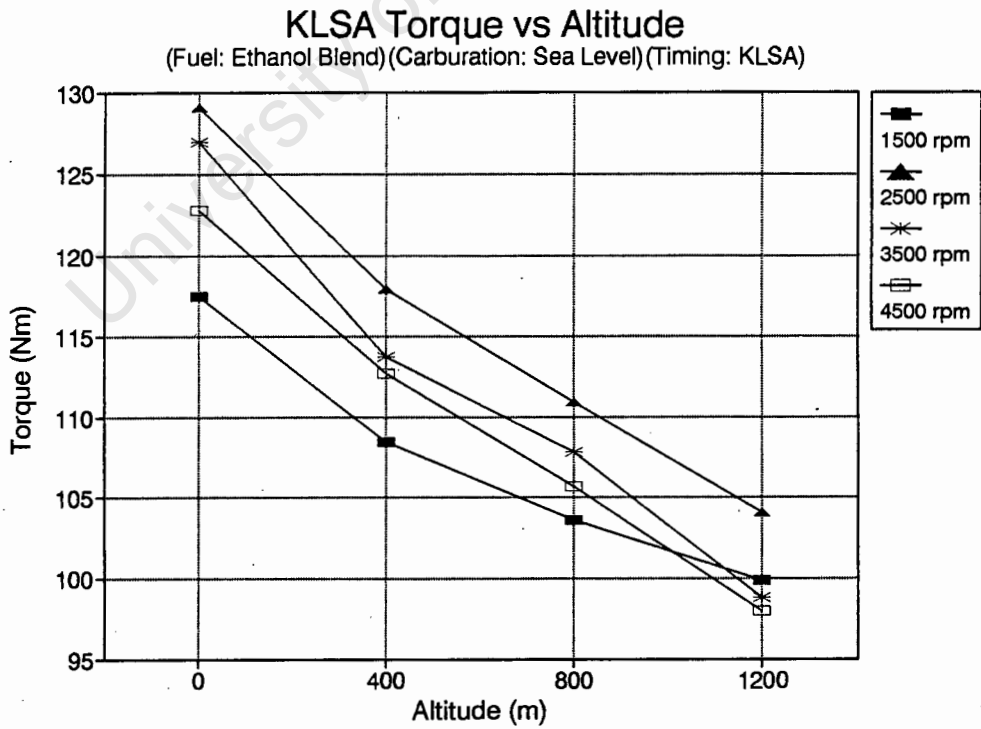
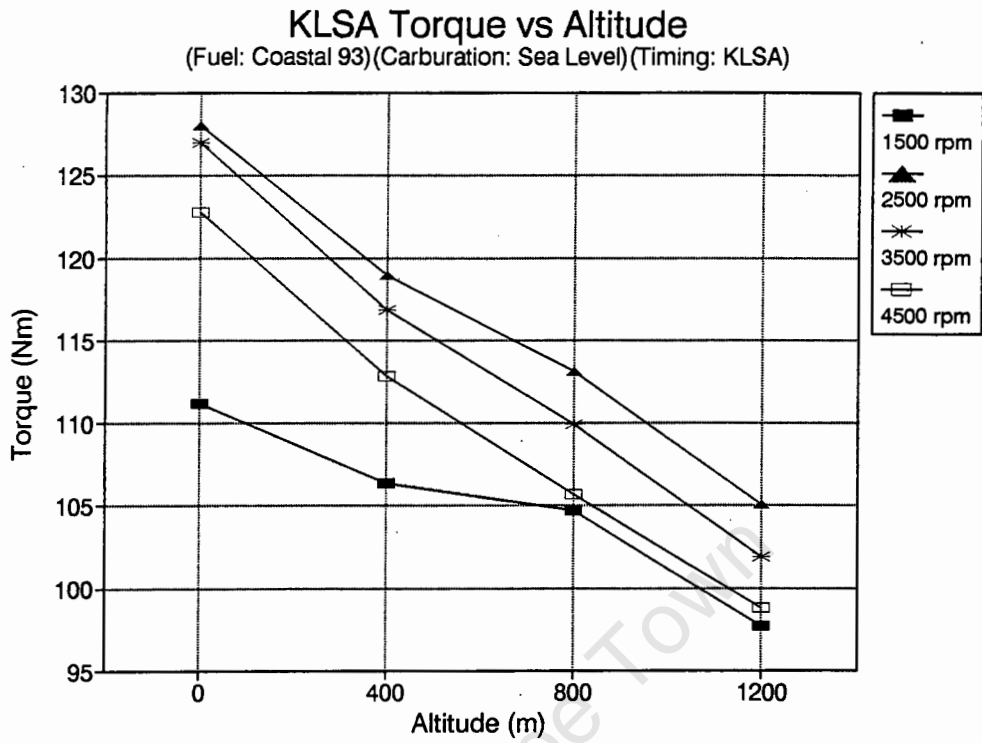


Figure E.22 Effect of altitude on KLSA torque with sea-level carburation setting

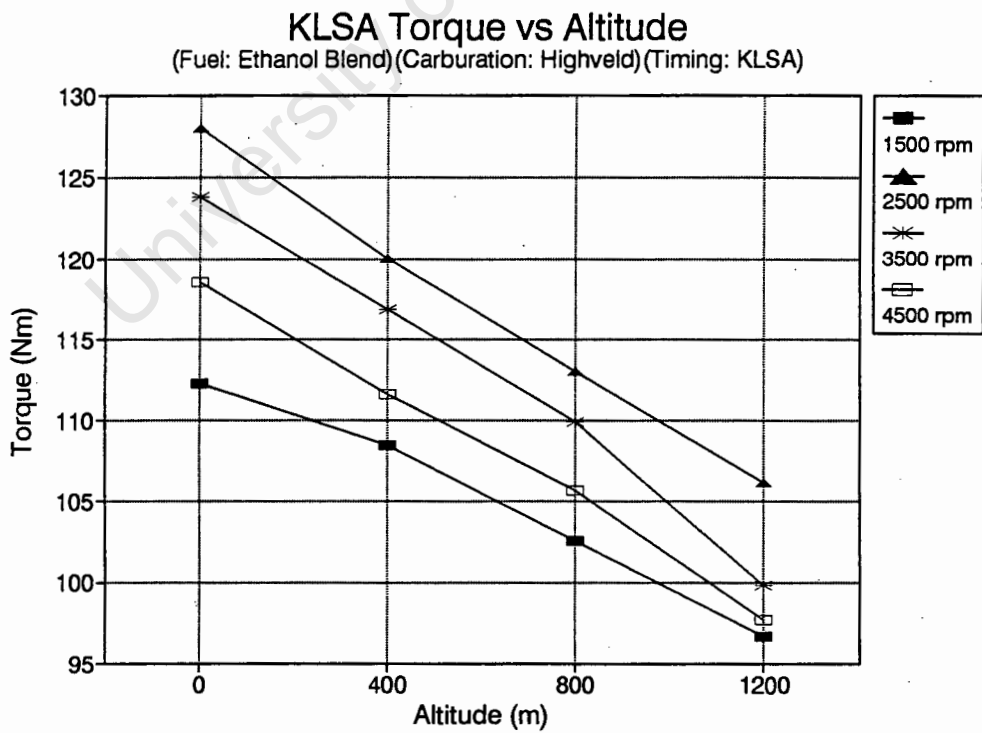
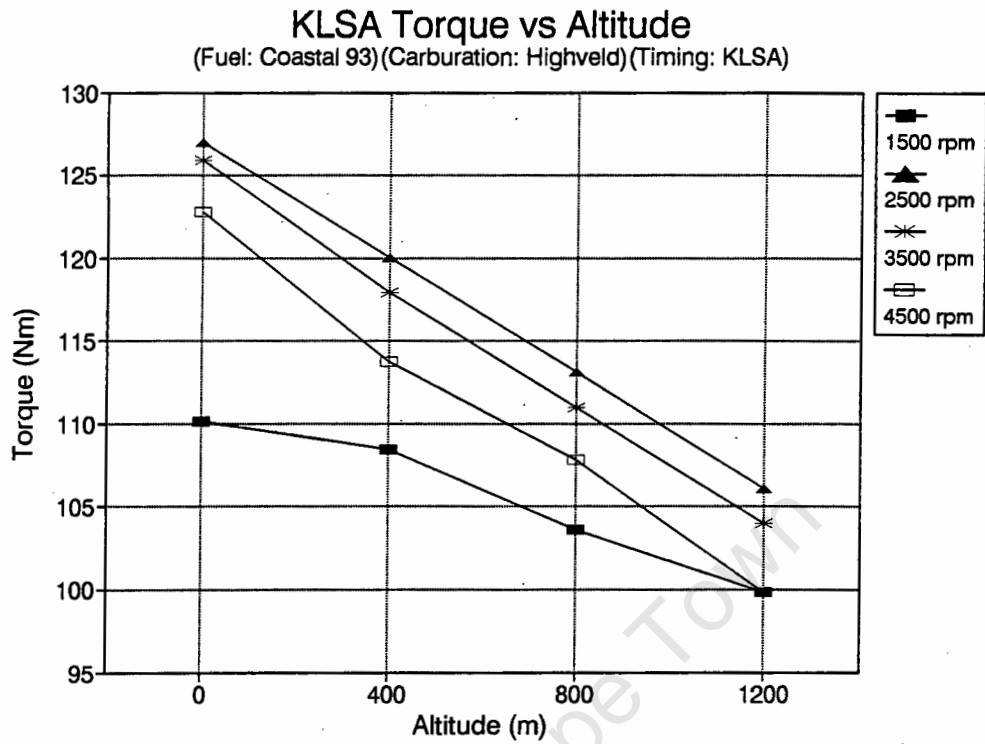


Figure E.23 Effect of altitude on KLSA torque with Highveld carburation setting

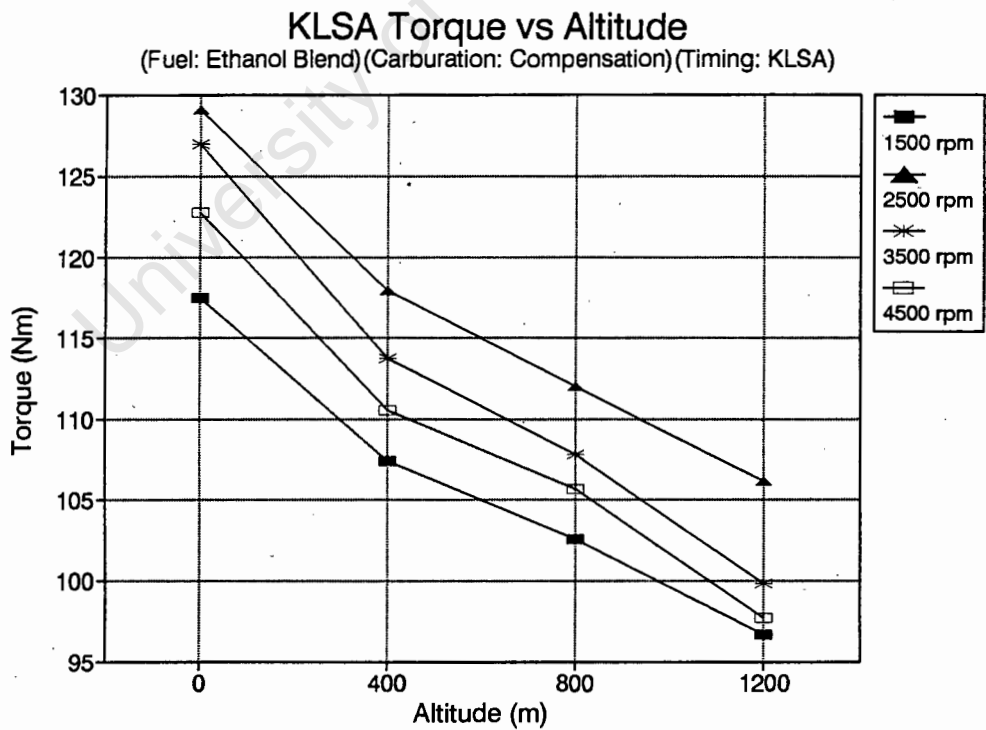
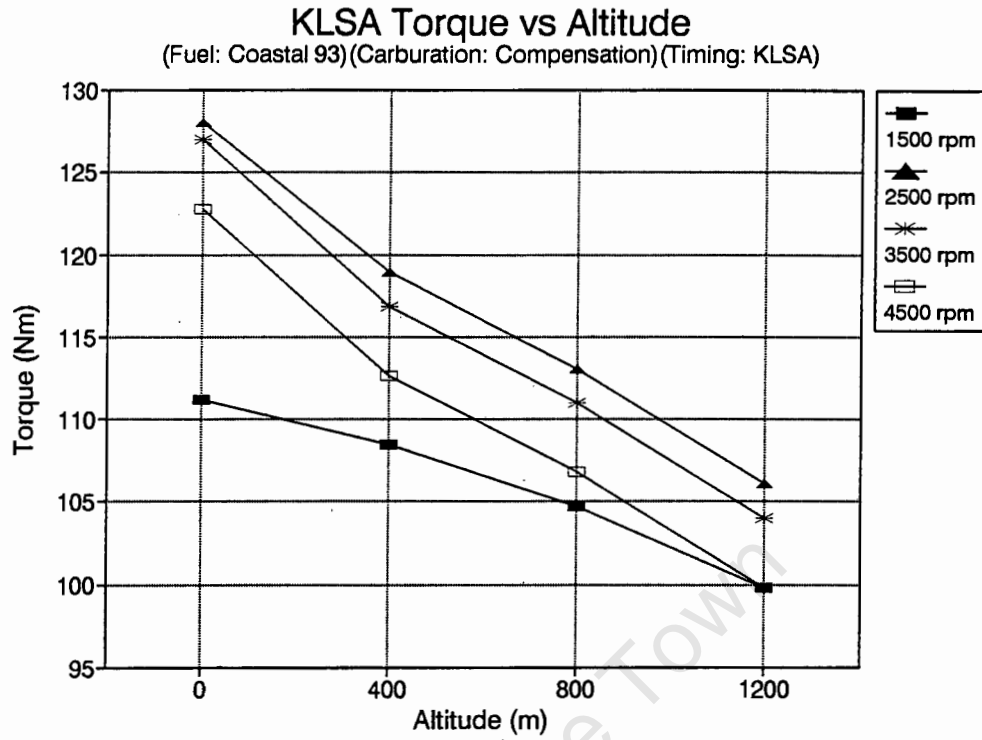


Figure E.24 Effect of altitude on KLSA torque with altitude-compensation carburatation